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Economics and Energy Conservation in the Design of New Single-Family Housing

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ECONOMICS AND ENERGY CONSERVATION IN THE DESIGN OF NEW SINGLE-FAMILY HOUSING

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ABSTRACT

This report investigates the extent to which certain energy conservation modifications to the envelope design of a new, single-family house are economically justified for a wide range of climates and projected energy costs. The report provides background information on those factors that give rise to space heating and cooling loads in buildings and examines in greater detail than in previous reports the thermal interdependencies within and among envelope components that can greatly affect heating and cooling loads. Economic criteria for determining a minimum life-cycle cost building envelope design are formulated and a priority-ranking method is developed to assist in the calculation of these designs. An expanded version of the NBS Load Determination Program is used to calculate the annual heating and cooling requirements and maximum heating and cooling loads for a 1200 square foot, wood-frame house having a wide range of thermal improvements in 14 geographic locations. The report also provides a methodology for interpolating these results to climatic conditions other than the 14 analyzed. The analysis demonstrates that the optimal envelope design configuration varies over a wide range depending on climate, energy costs, and modification costs.

Keywords: Architecture, building design, cost-benefit analysis, economics, energy conservation, housing, insulation, space heating and cooling.

PREFACE

This report is one of a series documenting NBS research and analysis efforts in developing energy and cost data to support the Department of Energy/National Bureau of Standards Building Energy Conservation Criteria Program. The work reported in this project was performed under the Building Energy Performance Criteria project and supported by Task Order A008-BCS under DoE/NBS Interagency Agreement No. EA 77A 01-6010.

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The energy savings and economic value of making energy conservation improvements to existing housing have been well documented since the oil embargo of 1973-1974. An NBS report published at that time, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, provided the first systematic analysis of the costs and benefits of some of these conservation measures -- insulation, storm windows, and weatherstripping -- for a wide range of climates and energy prices. An important part of that study was determining the optimal usage of such measures from the standpoint of life-cycle costs. The study showed that, in general, homeowners could economically justify a much higher level of investment in energy conservation measures in existing housing than was indicated by industry, utility, consumer group, or government recommendations. The conclusions of that earlier NBS study are reflected in many current energy conservation recommendations for existing housing.

Similar implications can be drawn for new housing as well. By incorporating a number of energy conserving features into the building envelope design, prior to construction, the requirements for space heating in new single family residences can be reduced dramatically relative to those of most existing residences and unmodified new housing. These features begin with the increased use of attic, wall, and floor insulation; multiple glazing; and measures to reduce air infiltration. Additional design features include improved thermal storage capability; the shape and orientation of the house as well as the internal location of living areas; and the size, orientation, and management of windows. Cooling requirements can also be reduced substantially at the design stage, primarily through attic insulation, increased thermal mass, solar shading devices, and whole-house ventilation.

This report investigates the extent to which certain building envelope design modifications, primarily related to increased use of insulation and multiple glazing, are economically justified for the range of climates found in the United States and for a wide range of projected energy costs.

To carry out this analysis, economic criteria for determining the minimum life-cycle cost envelope design are formulated. Considerable attention is given to describing the interdependent relationships between and within the building components. A methodology, called "priority ranking," is developed to determine the incremental savings resulting from component modifications. The incremental reductions in heating and cooling requirements resulting from each successive modification are calculated based on the assumption that all the higher priority -- that is, more cost-effective modifications -- have been made. This approach has certain limitations, which are discussed, but it offers a reasonably accurate methodology for determining the optimal levels of thermal resistance in the envelope components.

The priority ranking methodology was used to develop estimates of optimal envelope component configurations for 14 geographic locations and four heating types in each of these locations. The guidelines that are developed also take into account construction costs and financial investment criteria relevant to homeowners.

This report represents a significant advance over previous work of a similar nature because the heating and cooling requirements and reductions in those requirements resulting from the modifications were estimated using a dynamic load determination program, NBSLD, instead of steady-state methods and aggregate climatic data. Actual hourly climatic data for each location examined were utilized and the results corrected for long-term climatic trends. In addition, the thermal interdependencies among the envelope components were examined to a greater degree than in previous reports.

Results of the thermal analysis are reported in considerable detail, including annual heating and cooling requirements, maximum heating and cooling loads, annual heating and cooling hours corresponding to changes in the envelope design, heat gain and loss through south-facing windows and the walls of the four major orientations during heating and cooling hours, and latent cooling requirements.

A number of significant conclusions are derived from this analysis including the following points:

1) Optimal envelope design configurations vary over a wide range depending on climate, energy costs, and modification costs. For example, optimal attic insulation resistances in houses with electric heat and air conditioning range from R-19 in Miami to R-49 in Minneapolis. If only heating reductions are considered, optimal attic insulation levels may be less than R-11 in locations with very mild winter climates.

2) Increasing the size of south-facing, double-glazed windows in a well insulated house will reduce heating loads in very few locations unless substantial internal mass is available to store the heat gained in non-heating hours and release it during subsequent heating hours. A substantial night setback of the thermostat during heating periods will increase the relative benefits of large south-facing windows compared to a uniform day-night thermostat setting.

3) The orientation of a house appears to have little effect on its heating requirements if the orientation and size of its windows are not changed. Instead, the total surface area of the house is more important. However, the orientation of the house during cooling periods significantly affects cooling requirements; the heat gain through north- and south-facing walls together is considerably less than that through walls facing east and west. Moreover, orienting windows and daily living areas toward the south side of the house would likely have more effect on annual heating requirements than the actual orientation of the house itself. Because the north-facing wall loses significantly more heat than the south-facing wall, serious consideration should be given to improving its thermal characteristics relative to those of the other walls in climates where heating loads predominate.

4) Modified heating degree day and cooling degree hour data can provide a useful and relatively accurate means of interpolating heating and cooling (sensible) requirements to other locations based on more precise calculations in known climates. In addition, these modified data can be used to correct the results based on Test Reference Year climatic data, to better reflect long-term climatic trends. These data can provide a means for establishing improved climatic classification schemes for use in establishing energy budgets or thermal performance guidelines for new buildings.

5) Reductions in annual heating requirements are generally more than proportional to reductions in maximum (or design) loads. Thus, methodologies which base reductions in heating requirements on reductions in design loads will underestimate the potential savings from envelope design modifications. The opposite is true for reductions in annual cooling requirements. This lack of direct proportionality may have significant implications with respect to equipment sizing and part-load operations.

Additional research is required to resolve certain technical and economic issues and these are outlined in the report. The technical issues are related to the ability to better quantify the effects of design changes on annual energy requirements, including improvements that are needed in NBSLD and similar load-estimating programs. The economic issues are related to determining optimal building designs with respect to space heating and cooling.

In summary, this report provides new insights into the economic and thermal aspects of energy conservation in new housing design; it provides guidelines that will be useful to homebuyers, homebuilders, architects, and utilities. The information in this report also can provide the technical background and data for government policies and strategies related to energy use in housing. However, the role of government in regulating energy use in buildings can be diminished if the general public recognizes the long-term cost advantages of energy conservation considerations in the design of new housing.

SI CONVERSION

In view of the presently accepted practice of the building industry in the United States and the structure of the NBS Load Determination computer program used in this report, common U.S. units of measurements have been used throughout this report. In recognition of the position of the United States as a signatory to the General Conference of Weights and Measures, which gave official status to the metric SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to:

NBS SP330, 1972 Edition, "The International System of Units" E380-72 ASTM Metric Practice Guide (American National Standard Z210.1).

Metric Conversion Factors

Length:	1 inch (in) = 24.4 millimeters (mm)
	1 foot (ft) = 0.3048 meter (m)
Area:	1 ft^2 = 0.092903 m^2
Volume:	1 ft^3 = 0.028317 m^3
Fluid Capacity:	1 gallon (gal) = 3.78541 liters (L)
Temperature:	1°F = 9/5°C + 32
Temperature Interval:	1°F = 5/9°C or K
Mass:	1 pound (lb) = 0.453592 kilogram (kg)
Mass per unit length:	1 lb/ft = 1.48816 kg/m
Mass per unit area:	1 lb/ft^2 = 4.88243 kg/m^2
Mass per unit volume:	1 lb/ft^3 = 16.0185 kg/m^3
Energy:	1 Btu = 1.05506 kilojoules (kJ)
Heat flow rate:	1 Btu/h = 0.293071 Watt (W)
U-value:	1 Btu/(ft^2)(h)(°F) = 5.67826 W/(m^2)(K)
R-value:	1(ft^2)(h)(°F)/Btu = 0.176110(m^2)(K)/W

1. INTRODUCTION

The energy savings and economic value of making energy conservation improvements to existing housing have been well documented since the oil embargo of 1973-1974. An NBS report published at that time, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis,[1] provided the first systematic analysis of the costs and benefits of some of these conservation measures -- insulation, storm windows, and weatherstripping -- for a wide range of climates and energy prices. An important part of that study was determining the optimal usage of such measures from the standpoint of life-cycle cost. The study showed that, in general, homeowners could economically justify a much higher level of investment in energy conservation measures in existing housing than was indicated by industry, utility, consumer group, or government recommendations. The conclusions of that earlier NBS study are reflected in current NBS energy conservation recommendations for existing housing.[2]

Similar implications can be drawn for new housing as well. By incorporating a number of energy conserving features into the building envelope design, prior to construction, the requirements for space heating in new, single-family residences can be reduced dramatically relative to those of most existing residences. These features begin with the increased use of attic, wall, and floor insulation; multiple glazing; and measures to reduce air infiltration. Additional design features include improved thermal storage capability; the shape and orientation of the house as well as the internal location of living areas; and the size, orientation, and management of windows.

Cooling requirements can also be reduced substantially at the design stage, primarily through attic insulation, increased thermal mass, solar shading devices, and whole-house ventilation. Several studies have examined some or all of these potential conservation features and have generally concluded that their increased use is warranted from both a conservation and economic standpoint.[3]

Initially, design improvements to reduce energy requirements in new housing will have a smaller impact on total national energy consumption than modifications

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1 S. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, BSS 64, National Bureau of Standards, Washington, D.C., 1974.

2 For example, see: M. Jacobs and S. Petersen, "Making the Most of Your Energy Dollars in Home Heating and Cooling," NBS Consumer Information Series 8, National Bureau of Standards, Washington, D.C., 1975.

3 For example see: J. C. Moyers, The Value of Thermal Insulation in Residential Construction: Economics and the Conservation of Energy, U.S. Atomic Energy Commission, Oak Ridge National Laboratory, 1971; Residential Energy Consumption, Single-Family Housing (Final Report), HUD-PDR-29-2, Hittman Associates, Inc., Columbia, MD, 1975; and S. Petersen, Retrofitting Existing Housing for Energy Conservation.

to existing housing because, currently, the proportion of existing housing to new housing is greater. But by the end of this century, nearly one-third of the housing in the United States will have been constructed since the oil embargo of 1974,[1] so that the impact of conservation in new housing in response to higher energy prices will be substantial.

In addition, there is a substantially greater potential for reducing heating and cooling energy requirements in new housing compared to existing housing. From an economic viewpoint, the useful life over which conservation costs can be amortized is often longer for new housing and these additional costs can generally be included in a long-term mortgage. From a technical viewpoint, the design opportunities to reduce energy use are more varied. For example, structural modifications which would be prohibitively expensive to make in existing housing can often be made at a relatively small cost increase in new housing. Structural modifications allow greater capacity for insulation in walls, ceilings, and floors; better window designs and less expensive methods for triple glazing; tighter construction to reduce air leakage; better locations for ductwork; more efficient heating and cooling equipment; and better zoning of interior areas.

1.1 PURPOSE AND SCOPE

With these considerations in mind, the primary purpose of this report is to investigate the extent to which certain building envelope design improvements, especially those which involve increased costs at the time of construction, are economically justified on a life-cycle basis for the range of climates found in the United States and for a wide range of projected energy costs. Energy conservation guidelines are developed which take into account climate, energy costs, construction costs, and financial investment criteria relevant to homeowners. Such guidelines can be of considerable help to homebuyers, homebuilders, architects, and utilities. This information also can provide the technical background and data for government policies and strategies related to energy use in housing. It is hoped, however, that the role of government in regulating energy use in buildings can be diminished if builders and homebuyers recognize the long-term cost advantage of increased energy conservation considerations in the design of new housing.

A secondary purpose of this report is to demonstrate the fundamental economic relationship between energy conservation and energy consumption in building design. This relationship is established by using life-cycle cost analysis as a tool in the actual design process. Life-cycle cost considerations are systematically incorporated into the design process to determine design configurations that minimize life-cycle costs. This requires detailed knowledge of both the economic and technical interrelationships that characterize energy use in buildings, not only for the building as a whole, but for each of its energy-related components.

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[1] Data Resources, Inc., Energy Review, Lexington, MA, Winter 1980-81.

The economically optimal envelope designs developed in this report with respect to heating and cooling loads are based on a 1200 square-foot, single-family, ranch-style house. However, the conclusions of this report with respect to optimal insulation levels and multiple glazing are generally valid for a wide range of wood-frame house sizes. Guidelines for insulation in masonry walls of single-family houses are reported separately.[1]

The National Bureau of Standards Load Determination (NBSLD) program is used to analyze the heating and cooling loads corresponding to the various design alternatives examined in this report. NBSLD simulates the hourly dynamic thermal response of the building envelope and provides results that are sensitive to solar gains, internal heat release, occupancy schedules, air infiltration and hourly climate data. In addition, NBSLD makes it possible to model interdependent relationships among the envelope components in a manner not generally possible with less sophisticated approaches to load calculation.

The cost data used in the analysis were provided under contract in 1977 by a source close to the housing construction industry, the NAHB Research Foundation.[2] These data were adjusted to reflect increases in construction costs to 1979, the year in which the major part of this report was completed.

Annual heating and cooling requirements corresponding to a wide range of design modifications and climate conditions are included in addition to calculations of actual energy savings. Eventually this type of data may prove useful in the development of "energy budgets" to be used in performance criteria for new housing.

Basically, the report emphasizes the design of the thermal envelope of a conventional dwelling unit. Although the report does not consider design alternatives for heating, ventilating and air conditioning (HVAC) equipment, the effect of the seasonal efficiency of such equipment on both annual energy use and the economically optimal envelope design is an important element in the analysis. The report does not deal with optimal envelope configurations that incorporate solar heating and cooling equipment, although some implications for passive solar designs are discussed. Nor does this report investigate window management techniques or daylighting schemes that can be incorporated into the envelope design.[3]

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[1] See S. Petersen, K. Barnes and B. Peavy, Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single-Family Housing, BSS 134, National Bureau of Standards, Washington, D.C, 1981.

[2] The NAHB Research Foundation is a wholely owned subsidiary of the National Association of Home Builders.

[3] Advanced versions of the NBSLD computer program needed for the dynamic analysis of daylighting and window management schemes were not available at the time this report was prepared. Since that time a new version of NBSLD that incorporates daylighting analysis has been developed. See T. Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, (Revised) NBSIR - Draft Report, National Bureau of Standards, Washington, D.C., April 1981.

1.2 ORGANIZATION

The report begins with section 2, which provides background information on those factors which give rise to space heating and cooling loads in buildings. This section describes the fundamental principles of heat transfer through the building envelope and the interdependent relationships within and among envelope components that affect heating and cooling loads. Performance guidelines for designing a more energy-efficient building envelope are outlined. In section 3, the economic criteria for determining the minimum life-cycle cost envelope design are formulated. A priority ranking method to assist in the calculation of the minimum life-cycle cost design is developed. Section 4 describes the prototype single-family, detached house used in the thermal analysis and the modifications to reduce conductive heat transfer through the building envelope that are analyzed.

In section 5, the expanded output version of the NBSLD program is described. Section 6 discusses the results of the thermal analysis in some detail. These results include data for 14 different locations throughout the United States. These locations were selected because they cover a wide range of climates and, hence, heating and cooling requirements. Section 7 correlates the heating and cooling requirement data for the prototype house with aggregate climatic data. This provides a basis for interpolating the results of the thermal analysis to other locations. In section 8, the economic assumptions used to estimate the cost effectiveness of the modifications considered are discussed. A generalized computational methodology is presented which allows the reader to change these assumptions to better reflect specific requirements. Conclusions and recommendations for further research are discussed in section 9.

2. ENVELOPE DESIGN TO CONSERVE ENERGY: TECHNICAL ASPECTS

In this section, the basic terminology and concepts necessary for understanding how building design affects space heating and cooling requirements are defined. Design strategies for reducing such requirements are then examined. Lastly, this section describes the interdependencies between building envelope components and explains how these interdependencies affect heating and cooling loads.

2.1 BASIC DEFINITIONS

Buildings are designed to satisfy a large number of performance objectives, ranging from providing basic shelter to expressing personal aesthetic preferences. One of the most basic performance objectives for an occupied building is providing thermal comfort. This report shows how this objective can be satisfied at minimum life-cycle cost, while simultaneously satisfying the other building performance criteria imposed by the occupant.

Thermal comfort has been defined from a physiological viewpoint as that state of mind which expresses satisfaction with the thermal environment.[1] In general, the major determinants of thermal comfort in buildings are clothing, activity of occupants, dry-bulb air temperature, relative humidity, air movement, and mean radiant temperature. The first two factors are controlled entirely by the occupant; the last four depend largely on the overall building design and the mechanical heating and cooling systems within, although these may be controlled to some extent by the building occupants.

Space heating or cooling loads occur when the HVAC equipment must be operated in order to satisfy minimum thermal comfort requirements. Generally, the controls for HVAC equipment in houses are sensitive only to the dry-bulb air temperature. However, occupants can easily change the set point at which the equipment is turned on if the combined effect of the major comfort determinants falls outside of the comfort zone. In some houses, separate sensors and equipment (humidifier and/or dehumidifier) are provided for humidity control.

Space heating and cooling requirements are defined here as the integration of space heating and cooling loads over time.

Space heating and cooling loads and space heating and cooling requirements can be reduced both by improvements to the building design and changes in thermostat settings (lower for heating, higher for cooling). Purchased energy requirements can also be reduced through improvements in the conversion efficiency of the heating and cooling equipment; however, this report focuses only on the design of the building envelope.

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[1] "Thermal Environmental Conditions for Human Occupancy," ASHRAE Standard 55-74, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1974.

2.2 FUNDAMENTALS OF HEAT TRANSFER IN BUILDINGS

The building envelope is made up of components that enclose the conditioned spaces and through which thermal energy, or heat, may be transferred to, or from, the exterior. The envelope includes not only components through which thermal energy is directly transferred, such as walls and windows, but "buffer" components as well, such as attics, attached garages, and crawlspaces.

Heat is transmitted through the building envelope by three principal means: thermal conduction, air exchange, and radiation. Each of the three mechanisms plays an important role in determining heating and cooling loads; each can be significantly modified in the design process to reduce these loads. The relationship of each to space heating and cooling loads can be stated precisely in mathematical terms;[1] however, this is beyond the scope of this report. Instead a verbal description of each heat transfer mechanism is outlined to provide a consistent basis for the later discussion of design strategies to reduce space heating and cooling requirements.

2.2.1 Thermal Conduction

Thermal conduction is the process of heat transfer through a material medium in which kinetic energy is transmitted by particles of the material from particle to particle without gross displacement of the particles.[2] The driving force of conductive heat transfer is the temperature differential across the material medium. Under steady-state conditions, the amount of heat transferred through the medium is directly proportional to this temperature differential. However, under dynamic conditions, where the temperature differential fluctuates over time, the amount of heat transferred through the medium is modified by the thermal storage capacity of the medium.

Some envelope components (e.g., walls) may have a significant thermal storage capacity. Thus, conductive heat losses from (or gains to) the conditioned space should be measured at the inside surface of the envelope components. It is these surface losses or gains, sometimes referred to as surface "fluxes," which actually influence the air temperature and mean radiant temperature of the conditioned space. The usefulness of the thermal storage capacity of the envelope components should be measured primarily in terms of its ability to modify surface fluxes during actual heating or cooling periods; modification of surface fluxes during periods when there are no heating or cooling loads will have little effect on later heating or cooling loads.

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1 For a more precise statement of these relationships, see T. Kusuda, NBSLD, the Computer Program for Heating and Cooling Loads in Buildings, BSS 69, National Bureau of Standards, Washington, D.C., 1976.

2 ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, 1972, p. 533.

In addition to the building envelope itself, interior partitions and furnishings can act as thermal storage devices, moderating changes in interior air temperature by storing or releasing heat according to their own physical properties. As with the envelope components, the usefulness of this interior storage capacity also is measured primarily in terms of its surface fluxes during actual heating and cooling periods.

2.2.2 Air Exchange

Air exchange in houses results from air infiltration and exfiltration, ventilation, and the opening of doors during entry and exit. Air infiltration (exfiltration) is the uncontrolled inward (outward) air leakage through cracks and interstices in or around envelope components. Ventilation is controlled air exchange due to unpowered sources, such as open windows, and powered sources, such as kitchen and bathroom exhaust fans and whole-house ventilators. In general, the greater the wind pressure and the temperature differential between inside and outside, the greater the rate of air exchange due to any of these means.

Air exchange contributes to heating and cooling loads in two ways. The first is due to sensible heat loss or gain; that is, the heat loss or gain resulting from the difference between outside and inside air temperature. The second is due to latent heat losses or gains; that is, the amount of heat required to change the state of moisture in the air from liquid to vapor or vice versa. Control of relative humidity in the conditioned space requires the ability to add or remove latent heat from the air.

2.2.3 Radiation

Solar radiation is transmitted directly through the building envelope through transparent envelope components, such as windows, glass doors, and skylights. (Solar radiation incident on the exterior envelope surfaces is transmitted to the conditioned space by conduction and is therefore not considered here.) The transmitted solar radiation is made up of both direct (beam) or diffuse (scattered) radiation. Clear sheet glass transmits from 85 to 90 percent of the incident radiation between 0.3 and 3.0 microns (shortwave), but is virtually opaque to long-wave radiation above 3.0 microns.[1] Thus, when the shortwave radiation is absorbed by a surface within a room and then reemitted as long-wave radiation, the heat cannot escape directly. This characteristic of architectural glass is called the "greenhouse effect."

Solar radiation does not directly contribute to heating and cooling loads. First, it must be absorbed by the surfaces within a room, raising their temperatures. Some of this absorbed energy is released directly to the inside air, while some is stored for release at a later time or is lost by increased conduction through the building envelope. In addition, some of this thermal energy is reradiated to other surfaces in the room where it is reabsorbed. Thus, not

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[1] ASHRAE Handbook of Fundamentals, p. 394.

all of the solar gain transmitted into the conditioned space is instrumental in reducing heating loads or in increasing cooling loads.

The extent to which solar heat gains actually affect these loads depends on (1) the extent to which heating or cooling loads exist during hours when solar radiation is transmitted into the building, (2) the ability of the building envelope to resist changes in conductive heat transmission due to increases in inside envelope surface temperatures, (3) the ability of the envelope, internal partitions, furnishings, and air to store the heat gain from solar radiation in order to reduce or eliminate potential heating loads at a later time or to increase or initiate cooling loads at a later time, and (4) the extent to which heat gain by solar radiation in one room of a building is circulated to other rooms in order to offset heating loads or increase cooling loads in those other rooms.

2.2.4 Radiation Exchange and Convection

In addition to heat transfer through the building envelope, heat transfer within the conditioned spaces can have a significant impact on heating and cooling loads. Heat transfer within the conditioned spaces occurs by two principal means: radiation exchange and convection. Radiation exchange occurs when two interior surfaces having different temperatures "see" one another. Thermal energy radiates from the warmer surface to the colder surface, reducing the temperature of the former and increasing the temperature of the latter until an equilibrium is reached (although not generally the same temperature). Because internal radiation exchange can influence the rate of heat loss or gain through the building envelope, it is of some concern in the design process. For example, during heating periods the warmer interior partitions will radiate to the colder inside surfaces of the building envelope. This in turn raises the temperature of the envelope surfaces and increases conductive heat losses. This heat transfer mechanism gives rise to some interdependence among the various components of the building. As the envelope components are better insulated against conductive heat transfer, both the temperature differentials and the rate of conductive heat loss diminish, so that the interdependence due to radiation exchange diminishes as well. However, window surfaces, which tend to be colder than the other room surfaces during heating periods, are still significant sources of this interdependence.

Heat transfer by convection, or air movement within the room, is also important. In general, the greater the temperature difference among the various room surfaces, the greater the rate of convection. Convective currents can have a significant effect on the rate of heat transfer between the air and the room surfaces; they also can create uncomfortable drafts. As with radiation exchange, as all of the envelope components are better insulated the temperature differences among the room surfaces decrease and the effect of convection on heat loss and comfort is decreased as well.

2.3 SPACE HEATING AND COOLING LOADS

Space heating and cooling loads result when the thermal comfort criteria of the building occupants are not satisfied by the moderating effects of the building

itself. In such cases, mechanical equipment must be used to reestablish or maintain thermal comfort. This mechanical equipment generally adds or removes sensible and latent heat to or from the air until comfort requirements are reestablished. In some cases, a radiant heat source, rather than direct warming of the air, is used to satisfy thermal comfort criteria during heating periods.

The existence and size of a space heating or cooling load do not depend entirely on the rate at which thermal energy is transmitted through the building envelope and out of, or into, the conditioned space. Other factors which affect space heating and cooling loads are internal heat release from occupants, appliances, hot water usage, and lights. In addition, heat release from massive interior partitions and furnishings, in which excess thermal energy may have been stored from previous hours, can help offset heat losses through the building envelope. If such massive storage media have been cooled below the indoor ambient temperature during previous hours, they also may be instrumental in offsetting cooling requirements.

2.3.1 Space Heating Loads

Space heating loads result when the net rate of heat loss from the conditioned space at the minimum acceptable indoor temperature exceeds the rate of instantaneous heat gain from internal heat release sources. Over the course of a year, the number of hours in which space heating loads occur can be reduced by modifying the building envelope to reduce conductive and infiltrative heat losses and/or to increase solar gains. This reduction occurs because internal heat gains can completely offset net heat losses during more hours of the year.

A key element in the evaluation of many design modifications is determining the actual hours in which heating loads occur. Modifications to the building envelope which reduce net heat losses from the conditioned space are primarily useful only to the extent that they do so during periods when heating loads are incurred. For example, increasing the area of south-facing windows in order to increase midday solar gain during the winter months is primarily useful only to the extent that there are heating loads to offset during those hours,[1] unless the increased solar gain can be stored internally and recovered at a later time when heating loads do exist. If the house is designed with relatively high levels of insulation and is relatively tightly constructed to minimize air infiltration, there will be many fall, winter, and spring afternoons when no heating loads exist and thus an increase in solar gain due to an increase in window size may not be useable in reducing heating losses. On the other hand, the increase in window area will increase conductive heat loss and, therefore,

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[1] To the extent that this increased solar gain may improve thermal comfort conditions above the minimum acceptable conditions, this increased gain may have some value to the occupants. In addition, the increased daylight may reduce the need for artifical lighting. The interrelationship between window area and daylighting benefits is discussed in T. Kusuda and B. Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, BSS 109, National Bureau of Standards, Washington, D.C., 1978.

will increase heating loads and may even increase the number of heating load hours during periods when sunlight is not available.

Proper evaluation of both solar gains and internal heat storage, therefore, requires that the calculation of heating and cooling loads be based on relatively short time intervals (usually one hour or less) rather than daily, monthly, or seasonally.

2.3.2 Space Cooling Loads

Space cooling loads result (1) when the rate of heat gain from internal sources and solar radiation is greater than the net rate of heat loss (if any) from the conditioned spaces at the maximum acceptable indoor temperature, or (2) when there is a net heat gain into the conditioned space at the maximum acceptable indoor temperature. Thus, space cooling loads may exist even when the outdoor temperature is lower than the indoor temperature.

Although internal heat and solar gains reduce heating loads, they increase cooling loads; in well insulated houses they may make up half of the annual cooling requirements. When natural ventilation is not used, the number of hours annually in which space cooling loads occur may actually increase as the building envelope is better insulated. The increase in load hours will generally occur during those periods when the outdoor temperature is lower than the indoor temperature but not low enough to completely offset the internal and solar heat gains. To a large extent, this undesirable effect of otherwise energy conserving design modifications can be offset by increasing ventilation rates. However, poor air quality, external noise, or high humidity levels may restrict the practicality of such actions.

As indicated earlier, space heating and cooling loads integrated over time are referred to as space heating and cooling requirements. Typically, space heating and cooling requirements are expressed in annual terms. While maximum (or "design") hourly heating and cooling loads are important for selecting HVAC equipment capacity, annual heating and cooling requirements are more relevant in determining the long-term energy requirements for operating the building and the cost effectiveness of design modifications to reduce these requirements. Numerous simplified methods for estimating annual energy requirements have been developed. However, accurate calculation of annual heating and cooling requirements and corresponding purchased energy requirements generally requires an hour-by-hour load analysis (or an analysis based on even shorter time intervals).[1]

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[1] Newer load calculation methods using modified degree data and solar gain data are providing reasonably accurate results. However, these methods are only now being made available for general use and were not available when this report was initiated.

2.4 DESIGN STRATEGIES FOR REDUCING HEATING AND COOLING REQUIREMENTS

There are numerous design modifications compatible with the basic performance objectives of single-family housing that can significantly reduce long-term space heating and cooling requirements. Such design modifications may reduce the capacity requirements of mechanical heating and cooling equipment as well. To some extent, design modifications for reducing heating requirements will also reduce cooling requirements. However, in some cases these design strategies are incompatible and a compromise solution must be determined. Economic criteria for selecting the economically optimal combination of envelope modifications will be discussed later, in section 3. The remainder of this section will outline building design strategies to reduce space heating and cooling requirements, based on the discussion presented above.

2.4.1 Space Heating Requirements

Design strategies to reduce space heating requirements include methods to

(1) reduce conductive heat losses;
(2) increase conductive heat gains (due to solar radiation on opaque envelope components);
(3) decrease air infiltration;
(4) increase solar gains through windows;
(5) circulate internal and solar heat gains to areas where they are most useful or, alternatively, to locate areas where these gains are most needed (e.g., family room) near the source of these gains; and
(6) to increase the thermal storage capacity of the building and its furnishings.

Although all these design strategies can substantially reduce space heating requirements, some are incompatible with conventional housing designs. For example, reducing conductive heat losses and increasing conductive heat gains cannot both be accomplished unless the conductance of the envelope components can be changed in place. (This process has been demonstrated using plastic beads of insulation that can be moved in and out of a wall or window. However, this is not currently practical in conventional housing.)

2.4.2 Space Cooling Requirements

Design strategies to reduce space cooling requirements include methods to

(1) reduce conductive heat gains;
(2) increase conductive heat losses (where the outside surface temperature is lower than the inside surface temperature);
(3) decrease infiltration if the outdoor temperature is above the indoor temperature;
(4) increase ventilation if the outdoor temperature is below the indoor temperature and the air quality is acceptable;
(5) decrease solar gains;

(6) decrease internal heat gains by venting to the outside, the selection of more efficient equipment and appliances, or the isolation of equipment and appliances from the conditioned space; and

(7) increase the thermal storage capacity of the building and its furnishings if flushing with cool night or morning air is practical before the outdoor air temperature warms up.

Depending on the outside temperature, the first two strategies may be somewhat incompatible if conductive heat gain and heat loss occur through the same envelope component. Otherwise, all other strategies are compatible with conventional building design.

2.4.3 Inconsistencies in Design Strategies

Two major inconsistencies arise when a house is being designed to reduce both heating and cooling loads. A design that will reduce conductive heat losses and hence heating loads will work against increasing conductive heat losses and hence cooling loads when the outside temperature is lower than the inside temperature. Similarly, increases in solar heat gains and internal heat gains are desirable in terms of reducing heating loads, but are undesirable for reducing cooling loads.

The first of these is the most serious with respect to heat losses through floors. Conductive heat losses through the floor to unheated spaces below can increase heating loads substantially during heating periods and reduce cooling loads substantially during cooling periods. Designing a floor that has a variable resistance to heat transmission is not currently practical; thus a design compromise must be reached based on the net annual impact on heating and cooling expenditures attributable to floor insulation.

Conductive heat losses through other envelope components during actual cooling periods are not generally significant if natural ventilation is used when outdoor temperatures are lower than indoor temperatures. However, if natural ventilation is not provided when outdoor temperatures fall below indoor temperatures, an increase in the thermal resistance of walls, window, and doors will likely increase cooling loads.

The design inconsistencies concerning solar heat gains can be resolved largely by using selective shading devices, either outside (e.g., awnings or roof overhang) or inside (e.g., blinds or drapes). External shading devices tend to be more effective than internal shading devices since they absorb or reflect solar radiation before it reaches the building envelope.

The treatment of internal heat gains depends largely on their source. Some sources of internal heat gains can be vented rather easily (e.g., clothes drier, bathrooms, kitchens) when it is advantageous to do so. Operational decisions (e.g., deciding not to bake or to take a hot bath during cooling hours) can reduce the effects of internal heat gains as well. Thus the differential effects of solar and internal heat gains can be largely alleviated by careful design procedures and selective operational strategies.

There is no question that space heating and cooling requirements in buildings can be reduced significantly at the design stage by implementing these design strategies. However, whether such reductions are worthwhile to the user depends on the dollar value of the energy saved and the cost of implementing those strategies. In section 3, economic decision-making criteria for selecting the most cost-effective building design will be discussed.

2.5 INTERDEPENDENCE WITHIN AND AMONG BUILDING COMPONENTS

A key factor to consider in calculating the change in space heating and cooling requirements (and the corresponding change in purchased energy requirements) due to modifications to envelope components is interdependence within and among building components. Interdependence within components occurs when the effects of a design modification to a component are dependent on the overall design of that component. Interdependence among envelope components occurs when the modification of one component affects the thermal and/or energy-related performance of another. In addition, interdependence between the overall envelope design and the heating and/or cooling equipment performance can have a significant effect on actual purchased energy requirements. As a result, an accurate calculation of the change in purchased energy requirements due to the modification of any given energy-related building component requires that the design of all the other components be considered simultaneously.

2.5.1 Interdependence Within Envelope Components

Interdependence at the envelope component level is especially strong with respect to changes in the rate of heat transmission of those components. For example, the reduction in heat transmission through an exterior wall resulting from the use of insulation inserts in the exterior siding (e.g., R-3 polystyrene) depends to a large extent on the overall thermal resistance of that wall before the insulated siding is added. Table 2.1 provides an example of the change in the rate of thermal transmission for a wall due to an increase in the thermal resistance of the exterior siding for two alternative wall designs, one without and one with insulation in the wall cavity (R-0 and R-11 respectively). In the former case the effect of insulated siding on the rate of heat transmission (U) is nearly five times greater than the latter (0.081 and 0.017, respectively). Because this interrelationship is so strong, it cannot be overlooked even in simple modeling approaches that are used to estimate reduced space heating and cooling requirements due to design modifications.

2.5.2 Interdependence Among Envelope Components

There are two types of interdependence among envelope components: "thermal" interdependence and "load" interdependence. Thermal interdependence relates the change in thermal performance of a modified component to the thermal performance of the other envelope components. Load interdependence relates the change in net heat transmission due to the modification of the building envelope to an actual change in space heating or cooling requirements. These interdependent relationships are often overlooked in simplistic analyses and therefore are examined further at this point.

Table 2.1 Change in Time-Rate of Heat Transmission (U) Through Alternative Frame Wall Systems[a] Due to Insulated Siding

	Cavity Insulation	
	R-0	R-11
U-value of Uninsulated Siding	0.208	0.081
U-value of Insulated Siding (R-3)	0.127	0.064
Change in U-value	0.081	0.017

[a] Based on Table 4A, Coefficients of Transmission (U) of Frame Walls, p. 365, ASHRAE Handbook of Fundamentals (20 percent framing factor used).

Thermal interdependence has three primary causes: (1) radiation exchange among the interior surfaces of the envelope; (2) convection currents on the inside surfaces of the envelope; and (3) solar radiation transmitted through one component (e.g., windows) and reflected or absorbed by other inside envelope surfaces. Each of these can influence heat transmission through unmodified envelope components, thereby changing the net effectiveness of any component modification. As noted in section 2.2, this interdependence diminishes as the overall envelope is better insulated.

Load interdependence results from the fact that a component modification can only reduce a heating or cooling load at any given time if a load actually exists at that time. For example, as the building envelope becomes better insulated and tighter in terms of infiltration characteristics, the hours in which heating loads exist decrease significantly. (This effect is shown for the prototype house in table 6.9, p. 70.) This is because internal and solar gains can completely offset envelope heat loss at a lower outdoor temperature. Any further reduction in envelope heat loss can save energy only in the remaining heating hours. Thus whether or not a modification to a given component will reduce a heating load in any hour depends on the thermal integrity of the overall building envelope.

Similarly, the total number of cooling hours depends on the overall thermal integrity of the building envelope. However, if air conditioning is used only in hours when the outdoor temperature equals or exceeds the indoor temperature, the number of cooling hours will stay relatively constant as the overall rate of thermal transmission is decreased since internally generated heat must be removed regardless of the envelope design. Under such conditions cooling load interdependence is not nearly as significant as heating load interdependence.

2.5.3 Interdependence Between Space Heating and Cooling Loads and Equipment Efficiency

Finally, the interrelationships between space heating and cooling loads and the conversion efficiency of the heating and cooling equipment must be considered. Assuming that these loads can be accurately calculated, purchased energy requirements can be determined if the conversion efficiency of the heating and cooling equipment is known.

However, the conversion efficiency of the equipment depends in part on the heating or cooling load and the indoor and outdoor temperatures. Thus, as the heating loads are decreased, the average heating equipment efficiency may change as well, due to an increase in part load operations and the elimination of operations at the higher outdoor temperatures when steady-state efficiencies are the highest. This effect can be offset somewhat by reducing the heating equipment size to better reflect reduced design capacity requirements. For the cooling loads, the reduction in design capacity requirement is more than proportional to the reduction in average cooling load size, which tends to reduce part-load operations and improve the seasonal performance of properly-sized cooling equipment.[1]

All calculations throughout the remainder of this study assume that the capacity of the heating and cooling equipment is sized to the design heating and cooling loads using the best available sizing criteria. Furthermore, it is assumed that for small changes in annual heating or cooling requirements the change in equipment efficiency is negligible. Future studies should be undertaken to study the effects of envelope design changes on equipment efficiency.

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[1] These reductions in average space heating and cooling requirements and capacity requirements will be discussed further in section 6.

3. ENVELOPE DESIGN TO CONSERVE ENERGY: ECONOMIC ASPECTS

3.1 ECONOMIC ANALYSIS IN BUILDING ENVELOPE DESIGN

As stated earlier, space heating and cooling requirements in new buildings can be reduced greatly through a variety of design improvements. For example, the house pictured in figure 3.1 is a specially designed, 1200 ft^2 (plus basement) single-family dwelling that incorporates a number of energy conserving features. These features include R-38 attic insulation, R-23 wall insulation, triple glazing, large south-facing window areas, a fully insulated basement, and extensive measures to reduce uncontrolled air infiltration. The design heating load was so low for this house (approximately 16,000 Btu/hr) that a specially ordered heat pump was required to properly match its output capacity to the load.

From an economic viewpoint, two important questions must be considered in evaluating such an energy conserving building design:

(1) Could the same reduction in space heating and cooling requirements be achieved by an alternative, but thermally equivalent, envelope configuration at a lower conservation cost?[1]

(2) Is the thermal performance of the overall building the most cost-effective for the climate, energy costs, and the conservation costs prevalent at the building site? That is, could an alternative level of conservation reduce life-cycle heating- and cooling-related costs further.

Both of these questions are fundamental to the design process for new buildings. The first is important in determining the least-cost envelope configuration that satisfies the overall performance objectives of the building, including a given limitation on space heating and cooling requirements. The second question relates to the scale of the overall energy conservation objective. If the level of thermal performance achieved in the example above is appropriate for the climate and energy costs encountered at that building site, how much further should it be improved in more severe climates, or for alternate energy sources with higher unit costs (e.g., electric resistance heating in place of a heat pump or direct combustion of fossil fuels)? Conversely, if the building configuration is found to be economically unjustifiable for the conditions encoutered, to what extent should the overall thermal performance of the building be reduced?

Economic analysis is useful in finding deterministic solutions to both of these design problems. As energy and housing costs continue to increase, central heating and air conditioning become more prevalent, and supplies of the lower cost fuels (e.g., natural gas) are curtailed for new housing starts, the answer to these questions will become increasingly important.

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[1] "Conservation cost," as used here, includes all costs related to improving the thermal performance of the building over its expected life.

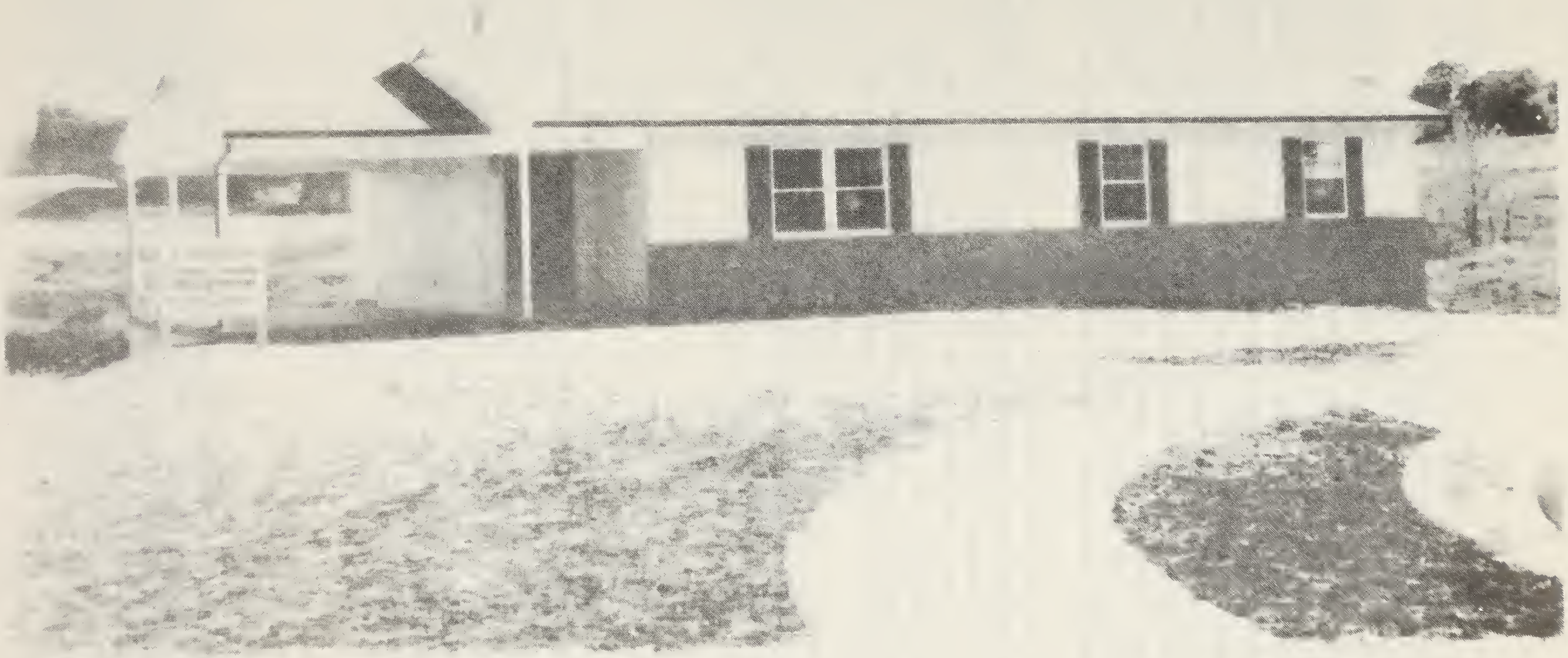

Figure 3.1 Super-Insulated Single-Family House Built by NAHB Research Foundation

3.2 ECONOMIC OPTIMIZATION IN ENVELOPE DESIGN

The configuration and scale problems addressed above arise because, in satisfying the given performance requirements of a building envelope,[1] it is often possible to substitute one design method for another. For example, in the configuration problem, where performance requirements include maximum permissible space heating and cooling requirements, one energy conservation technique (e.g., increased wall insulation) can usually be substituted for another (e.g., multiple glazing) without changing annual energy requirements or significantly affecting the overall building performance objectives. In the scale problem, where space heating and cooling requirements are variable, energy conservation improvements are substitutable for future energy consumption expenditures while continuing to satisfy the other building performance criteria.

Economic analysis can be used in the envelope design process to determine simultaneously the least-cost design configuration that is consistent with the least-cost scale of thermal integrity. If all design-related costs over the life of the building are considered (including energy conservation costs and energy consumption costs), this analysis will provide the lowest possible life-cycle cost design that will meet the performance requirements of the building. This resulting design is frequently referred to as economically "optimal."

This section discusses the basic principles of life-cycle cost analysis and the economic criteria for determining optimal design solutions. The remainder of the report focuses on the application of economic analysis to the energy conservation design of a prototype, single-family house for a range of climates and cost conditions.

3.2.1 Life-Cycle Cost Considerations in New Housing Design

Life-cycle cost analysis in building design requires that all expected costs related to the satisfaction of building performance requirements over the building's expected useful life be accounted for on a time equivalent basis, usually in present-value terms. These costs include not only "first" costs such as design, construction, and selling costs, but operating and maintenance costs as well, including utility bills, insurance, property taxes, repairs, and replacement and salvage costs, if any. The objective of life-cycle cost

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[1] These performance requirements include not only considerations for thermal comfort but for space, health, safety, structural integrity, and aesthetics. It must be recognized that such "requirements" are to some extent negotiable, in that user demand for them decreases as their costs increase relative to other user wants. However, the designer is generally provided with an objective assessment of the overall performance expectations of a building, and thus these may be viewed as fixed in the final stages of the design process.

analysis in building design is to minimize the sum of these costs while satisfying all building performance requirements.[1]

The life-cycle cost approach to design optimization provides an objective and consistent framework for analyzing the costs associated with energy use in buildings. Ideally, all energy-related costs incurred over the life of the building, from drawing board to demolition, should be considered. At the design stage, many of these costs can only be estimated, based on the most realistic assumptions available. But this does not diminish the importance of the life-cycle cost approach as a framework for decision-making. Most business decisions are made under varying conditions of uncertainty, but proper analysis can minimize the inherent risks associated with alternative actions. Assumptions made about future costs may be less than perfect, but it is better to make assumptions than ignore these costs entirely. Moreover, life-cycle cost analysis provides a consistent basis for sensitivity analysis with respect to those variables most likely to deviate from their expected values. Where probabilities can be assigned to the outcome of the important variables (e.g., to the long-term rate of increase in energy costs), design solutions can be found that minimize expected life-cycle energy-related costs.

Life-cycle cost considerations sharply contrast with design objectives based on minimum first cost, especially with regard to energy use in buildings. The emphasis on first cost has often been attributed to the speculative nature of new housing construction and the relatively rapid turnover of home ownership. Other explanations for the lack of concern for thermal integrity may be more appropriate. Historically, energy costs were decreasing relative to construction costs up until the early 1970's. Moreover, the widespread use of central resistance heating and air conditioning in new housing, both major consumers of electrical energy, is a relatively recent phenomenon. As a result, there was little incentive to consider energy conservation in housing design except in severe climates until energy prices began to rise and the availability of lower-cost heating fuels (i.e., natural gas) began to diminish.

This report assumes only one owner over the life of the house. While this assumption may appear to be unrealistic, it provides a deterministic scenario for estimating the costs and benefits of conservation features, with results generally comparable to those of an analysis that would focus on several shorter-term owners who are able to capitalize the unamortized portion of their conservation investment at the time of resale. As energy prices continue to increase, homebuyers will more likely be willing to pay more for houses with cost-effective conservation features, making it easier for sellers to regain their investment under such circumstances.

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1 For a more complete discussion of the life-cycle cost concept applied to building design see R. Ruegg, S. Petersen, and H. Marshall, Recommended Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, NBSIR 80-2040, National Bureau of Standards, Washington, D.C., 1980, and H. Marshall and R. Ruegg, Simplified Energy Design Economics, SP 544, National Bureau of Standards, Washington, D.C., 1980.

3.2.2 Evaluation of Future Costs and Savings

Before proceeding to the economic criteria for design optimization, a brief discussion is necessary on evaluating costs or savings incurred in different time periods. Specifically, costs or savings incurred in different time periods cannot be summed until they are adjusted to reflect the time-value of money. This process is generally referred to as "discounting." In this report, all future costs and savings will be discounted to their present value so that they may be directly compared to initial costs. Several mathematical formulas are useful in evaluating one-time future costs or savings or streams of future costs or savings over the life of a building in present-value terms. These formulas are provided in table 3.1. In addition, table 3.1 includes a "uniform capital recovery" formula which can be used to calculate the principal and interest payment required per time period in order to repay or loan over a specified length of time in uniform dollar amounts.

It is difficult to select an appropriate discount rate for general usage because individual circumstances differ considerably. The discount rate should reflect the real (i.e., net of inflation), after-tax, rate-of-return on the best alternative investment opportunity foregone, or the effective cost of borrowing, if borrowing is required to finance new investments such as energy conservation improvements. For many homeowners it is difficult to keep up with inflation on a before-tax basis, let alone on an after-tax basis, and thus their effective discount rate may be negative (i.e., less than zero percent). For those who must borrow to finance new investments and who are in a relatively low tax bracket (say 20 percent), a realistic discount rate based on the real cost of borrowing may be closer to four percent, assuming an 18 percent nominal borrowing rate and 10 percent inflation[1].

Frequently, the mortgage interest rate for new housing is used as the discount rate for energy conservation measures. However, this is not the appropriate rate unless it coincides with the homebuyer's personal discount rate. This is due to the nature of escalating energy costs, constant mortgage payments, and a down payment requirement. Where incremental savings in present-value terms, may be equal to, or only slightly greater than, the present value of the corresponding increase in monthly mortgage payments and the down payment, the homeowner may not realize a positive cash flow for some marginal conservation investments for a number of years into the life of the building. Since this negative cash flow may require postponement of other consumer goods purchases or alternative investments, the homebuyer's personal discount rate is the appropriate discount rate to use in the analysis of costs and savings.

When using this discount rate, the calculation of the present value of all mortgage payments, adjusted to reflect income tax deductions for interest payments, is the most accurate method of incorporating the mortgage interest rate into the analysis. Calculation of the present value of increased property taxes and insurance is also consistent with this approach.

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[1] $\dfrac{1 + 0.18\ (1-0.2)}{1.1} - 1 = .04$

Table 3.1 Discounting Formulas

Formula Name	Illustration	Use	Algebraic Form	
Single Present Value Formula (SPW)	$P? \leftarrow F$	To find P when F is known	$P = F \frac{1}{(1+i)^N}$	(3.1)
Uniform Present Value Formula (UPW)	$P? \leftarrow A + A \cdots A$	To find P when A is known	$P = A \frac{(1+i)^N - 1}{i(1+i)^N}$	(3.2)
Uniform Present Value Formula Modified (UPW*)	$P? \leftarrow A + A \cdots A$	To find P when A is escalating at rate e[a]	$P = A \frac{1+e}{i-e} \left(1 - \left(\frac{1+e}{1+i} \right)^N \right)$	(3.3)
Uniform Capital Recovery Formula (UCR)	$P \rightarrow A? + A? \cdots A?$	To find A when P is known	$A = P \frac{i(1+i)^N}{(1+i)^N - 1}$	(3.4)

Where:

P = a present sum of money.
F = a future sum of money to be received or spent.
i = an interest or discount rate for the period being considered.
N = number of interest or discountng periods.
A = an end-of-period payment (or receipt) in a uniform series of payments (or receipts) over N periods at i interest or discount rate.
e = rate of escalation of A in each of N periods.

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a To find P when A is escalating at a different rate over each of k escalation periods,

$$P = A\sum_{\ell=1}^{k} \left(\prod_{m=o}^{k-1} \left(\frac{1+e_m}{1+i_m}\right)^{n_m} \right) \left(\frac{1+e_\ell}{i_\ell - e_\ell}\right) \left(1 - \left(\frac{1+e_\ell}{1+i_\ell}\right)^{n_\ell} \right)$$

where e_ℓ = rate of escalation of A in period ℓ ($e_o = 0$),
i_ℓ = the interest or discount rate in period ℓ ($i_o = 0$), and
n_ℓ = length of period ℓ ($n_o = 0$).

Tables A-1, A-2, A-3, and A-4 in appendix A provide calculated factors for estimating the present value of mortgage payments and interest payments over the life of the mortgage loan, and the present value of energy expenditures (or savings) over a given useful lifetime, respectively. Appendix B provides a methodology for estimating the present value of property taxes and insurance for use in the life-cycle cost analysis of heating and cooling costs. Table B-1 in appendix B provides calculated factors for estimating increased property taxes and insurance liabilities consistent with the assumptions made in this report.

Total life-cycle costs (TLCC) related to heating and cooling energy usage over the useful life of the building can be calculated in simple terms as:

$$TLCC = IC + R - S + A + N + E \tag{3-5}$$

where:

IC = initial energy conservation investment costs (related to heating and cooling usage),

R = replacement conservation costs,

S = resale value (or salvage value) of conservation features at end of useful life,

A = annually recurring operating, maintenance, and repair (OM&R) costs (except energy) resulting from conservation investments,

N = non-annually recurring OM&R costs resulting from energy conservation investments,

E = energy costs,

and all costs are in life-cycle, present-value dollars.

A more comprehensive TLCC analysis will include adjustments to initial costs due to the financing of the investment and conservation tax credits (if any) plus increased property tax liabilities, so that equation (3-5) becomes

$$TLCC = C + R - S + A + N + E + P', \tag{3-6}$$

where

$$C = D + M - T_I - T_C \tag{3-7}$$

$$P' = P - T_P, \text{ and} \tag{3-8}$$

D = down payment,
M = present value of mortgage payments,

T_I = present value of income tax savings from interest,[1]
T_C = present value of conservation tax credits,
P' = net present value of increased property taxes,
P = present value of increased property taxes, and
T_P = present value of income tax savings from increased property taxes.

In the following subsection, the economic criteria for design optimization are based on the costs and savings incurred over the life of a building, discounted to present value in order to enable their comparison on a time-equivalent basis.

3.2.3 Envelope Design Optimization Criteria

Having established a consistent basis for calculating energy-related life-cycle costs in the previous subsection, basic economic optimization criteria can now be formulated for use in the design of building envelopes. These criteria are based on the substitutability of alternative energy-conserving design modifications both among one other and for building energy requirements. Although this report focuses on the thermal performance aspects of building envelope design, it is assumed throughout that the non-thermal performance requirements of each envelope component and the overall building design are satisfied at all times.

For the purposes of this report, the sum of average annual space heating and cooling requirements, Q, corresponding to a given building envelope design and the thermal comfort requirements of its occupants, is defined in terms of net thermal energy units delivered to the conditioned space, i.e., after on-site conversion and distribution losses, if any. The thermal performance of the individual envelope components is defined in terms of their ability to reduce net envelope heat losses during heating periods and net heat gains during cooling periods. As stated previously, the thermal performance of these components is somewhat interdependent and the change in Q attributable to a modification to one component may vary depending on the thermal performance of the other components. This interdependence must be considered in specifying the substitution of one conservation modification for another.

The envelope design optimization process begins only after the non-thermal performance requirements of the building envelope have been satisfied and the basic building design has been initially specified. It is assumed that the designer has considered the thermal performance aspects of the building in its basic design, based on prior knowledge and good judgment. However, it is also assumed that, up to this point, life-cycle cost considerations have not been specifically addressed in finalizing the envelope design with respect to thermal performance.

There are four criteria in the envelope optimization process; these are formulated below in a logical sequence for consideration in the envelope design process. In practice, however, all four criteria must be satisfied

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[1] Income tax savings depend on the marginal rate of income taxation (i.e., tax bracket) for federal, state, and local income taxes.

simultaneously in the final envelope design. The first three criteria apply to the determination of the least-cost design configuration[1] consistent with $\overline{Q}$, a prespecified design constraint on Q. ($\overline{Q}$ might be called an "energy budget" for space heating and cooling.) The fourth criterion provides the basis for selecting the level of $\overline{Q}$ that minimizes the total cost of energy conservation and energy consumption expenditures over the life of the building, while satisfying all thermal and non-thermal building performance requirements. As the optimal scale of $\overline{Q}$ changes, the least-cost envelope configuration consistent with that scale will change as well.

The first criterion in the envelope optimization process requires the determination of the least-cost design for any specified level of thermal performance over the practical range of consideration for each envelope component.[2] This involves a thermal analysis of the means and rate of heat transfer for each component and a cost-engineering analysis to determine the least costly method of reducing heat transfer. The thermal performance of an envelope component includes more than its overall thermal conductance and air permeability. Other factors affecting thermal performance that might be considered are: air temperature differentials from inside to outside, air movement across the surfaces, absorptivity and emissivity of the surfaces, radiation exchange to and from other components, shading and orientation of the component, and the thermal storage capacity of the component.

Essentially, this first criterion requires that for any desired level of thermal performance, materials (subcomponents) with lower costs per unit of thermal performance will be substituted for materials with higher unit costs until no further substitution is economically possible. Consistent with this step, less costly thermal insulation (e.g., mineral wool) is generally used instead of other more costly building materials (e.g., lumber) as a means of increasing the thermal resistance of an opaque envelope component beyond that needed for its basic structural integrity.

In some cases the structural design of a component must be altered to increase its thermal performance beyond some nominal level. In such a case, any increase in structural costs must be allocated to the cost of the additional thermal performance that it provides. Insulation materials with higher costs per resistance unit may be used if they provide the desired level of thermal

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[1] Cost here refers to the present value of all expenditures incurred in increasing the thermal integrity of the building envelope. This includes consideration for durability of materials, replacement and maintenance costs, taxes, and insurance. Salvage value may be properly considered here as a negative conservation cost. However, the salvage value of most building materials related to conservation is very small in present-value terms and can therefore generally be ignored if the analysis extends over the useful life of the building.

[2] Where thermal performance is continuously variable, the cost of increasing thermal integrity is best formulated in equation form. Where thermal performance is increased in discrete units, a cost schedule is more appropriate.

performance at a lower cost than that of a structural modification that can be avoided with their use. This sometimes leads to the use of relatively expensive "high efficiency" insulation materials such as plastic foams instead of less expensive conventional insulation materials with lower efficiency such as mineral wool and cellulose.

In some cases, the thermal performance of a component can be increased continuously or nearly continuously (e.g., loose-fill insulation in attics). In other cases, thermal performance can be increased only by discrete increments (e.g., double and triple glazing). In general, as the thermal performance of any component is increased, the total cost of that component is expected to increase as well. The rate at which the total cost of each component increases with improvement in its thermal performance plays an integral role in establishing its optimal configuration.

The second criterion in the envelope design optimization process requires the determination of the level of thermal performance for each component, given the combination of components in the basic envelope design, which satisfies the constraint $\overline{Q}$ at minimum total conservation cost. This criterion requires that the thermal performance of one component be increased and the thermal performance of others be correspondingly reduced as long as the cost of the former modification is less than the savings from the latter modifications. This substitution process is carried out among all the components until no further substitution is economically desirable. At this point, an economic balance has been achieved; that is, the last dollar spent on improved thermal performance for each component has the same effect in satisfying the constraint $\overline{Q}$. Any further substitution must increase the overall cost of achieving $\overline{Q}$. For example, the cost of increasing the thermal performance of the attic is generally less than that of exterior walls because of the structural modifications needed to increase the thermal resistance of walls. As a result, the least-cost envelope design will generally specify more attic insulation than wall insulation. However, the last dollar spent on both wall and attic insulation should produce the same energy savings. Where discrete increments are considered, such a balance may not be perfectly satisfied. However, as long as no further substitution will reduce conservation costs, the minimum cost solution has been determined.

The third criterion in the envelope design optimization process requires the determination of the least-cost configuration of components consistent with the constraint $\overline{Q}$. For example, wall areas might be substituted for window areas (or vice versa, according to orientation) in order to reduce the cost of satisfying $\overline{Q}$. In addition, a change in the aspect ratio or orientation of the envelope may also reduce the cost of satisfying $\overline{Q}$. Up to some point, it may cost less to modify the configuration of components to achieve $\overline{Q}$ than to improve the thermal performance of the individual components themselves. Thus, the substitution of configuration modifications for component modifications may further reduce the cost of satisfying $\overline{Q}$.

Non-construction costs may also have to be included in the determination of the least-cost envelope design. These costs are related to the building occupant's needs, both real and perceived. For example, a significant change in window

area may be unacceptable to the occupant, even if it reduces the purchase cost of a house. Or, in the case of modifying aspect ratios or envelope orientation, the resulting dimensions of the house may be impractical for the lot size or in terms of useful space arrangement. Estimating these costs is difficult, partly because they are intangible and partly because they vary from occupant to occupant. As a result, house designs (especially for speculatively built housing) are usually constrained by revealed market preferences.

As with the first and second criteria, substitutions should be made among components as long as these substitutions reduce the cost of satisfying $\overline{Q}$. Again, an economic balance is achieved in that the last dollar spent on each modification of component size will have the same effect in satisfying the constraint $\overline{Q}$. Any other configuration of envelope components will increase the total cost of satisfying that constraint.

At this point the basic economic criteria for determining the least costly envelope design consistent with $\overline{Q}$ have been defined. As stated earlier, all of these criteria must be satisfied simultaneously.

The fourth and final criterion in the envelope design process requires the determination of the optimal level of Q, $\overline{Q}_o$, that minimizes the total life-cycle cost related to the thermal comfort requirements of the building occupants. Essentially, this criterion requires the substitution of improvments in the thermal performance of the building envelope for energy usage wherever the incremental cost of the thermal improvements is less than the dollar value of the incremental energy savings realized. If the cost of the last units of thermal performance already exceeds their attributable savings, $\overline{Q}_o$ has been exceeded and the thermal performance of the building envelope must be reduced until incremental savings are equal to their incremental costs.

Now an economic balance is achieved between the cost of increased thermal performance and the cost of the energy resources used for space heating and cooling. That is, the last dollar spent on energy conservation (over the life of the building) has the same productivity (in terms of satisfying thermal comfort requirements) as the last dollar spent on energy consumption. No further change in the envelope design can reduce the total present-value, life-cycle cost of achieving the thermal comfort requirements of the building occupants.

This criterion requires that the incremental life-cycle dollar savings (in terms of reduced energy requirements) be calculated for each additional building envelope modification considered. These incremental savings are then compared with the incremental costs incurred on a present-value basis. All modifications with incremental savings greater than or equal to incremental costs are included in the optimal envelope design; modifications with incremental savings less than incremental costs are not.

This fourth criterion is central to any economic analysis of energy conservation in building design because it determines the extent to which design energy requirements should be tightened up in response to rising energy prices. For any given location, the greater the energy costs relative to conservation costs, the greater will be the optimal level of thermal performance

for the envelope and the lower will be $\overline{Q}_o$. Similarly, the greater the conservation costs relative to energy costs, the lower will be the optimal level of thermal performance and the greater will be $\overline{Q}_o$. The more efficient the heating and cooling equipment, the greater will be $\overline{Q}_o$; the less efficient the heating and cooling equipment, the lower will be $\overline{Q}_o$.

The fourth optimization criterion is stated somewhat differently than the previous ones. In the first three criteria the constraint $\overline{Q}$ was stated in terms of annual heating and cooling requirements, as measured in thermal energy units. In this last step, the constraint $\overline{Q}$ is not only released but heating and cooling requirements per se are no longer primary to the optimization process. Instead, the primary factor is the <u>cost</u> of the energy consumed (or saved) to satisfy the thermal comfort requirements of the occupants. The cost of that energy is a function of purchased energy prices and the efficiency of the space heating and cooling equipment. Moreover, the cost of energy used for heating may differ significantly from cooling costs, and the efficiency of the heating equipment may differ significantly from cooling efficiency. Therefore, the dollar value of a unit change in annual heating requirements may be quite different than a unit change in annual cooling requirements.[1] The first three steps in the envelope design optimization can be made more consistent with this last step if $\overline{Q}$ is expressed in terms of the dollar value of the average annual heating and cooling requirement instead of its thermal energy value. This redefined $\overline{Q}$ has more meaning from an economic standpoint than the previous definition, and will be used in determining optimal building envelope configurations in this report.

These steps in the envelope design optimization process have been presented in a logical order, but as stated earlier, all four steps must be satisfied simultaneously in the finalized design. If the thermal performance of each envelope component could be increased continuously at increased cost and the interdependent relationships among all the components could be modeled mathematically, the optimal design configuration could be directly determined by differentiation. However, because of the discrete nature of most component modifications (e.g., insulation batt resistances and multiple glazing), and the difficulty of specifying the interdependent relationships among components in mathematical form, an alternative methodology for design optimization must be developed. This is done in the following subsection.

3.2.4 Priority Ranking to Determine the Incremental Savings Resulting From Component Modifications

It would be a relatively easy task to determine the optimal envelope configuration if there were no interdependencies among the envelope components. First, the optimal thermal performance of each component would be determined individually, based on incremental savings and cost analysis, without regard

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[1] Note that in cases where a modification reduces heating requirements but increases cooling requirements, or vice versa, the net savings in dollar terms are used in finding the optimal energy-related component design.

to the overall envelope configuration. Then, substitutions of related component areas could be made (e.g., windows and wall areas), ignoring unrelated envelope components (e.g., ceiling and floor). This simplistic approach is often used when insufficient information regarding the interdependencies among envelope components is available.

Today, however, it is possible to quantify the effects of interdependencies among components to a considerable extent through the use of high speed computers, advanced computational algorithms, and hourly climatic data. When this type of analysis is carried out, computed reductions in heating and cooling requirements in a given building resulting from the modification of any one of its components will vary depending on the overall design configuration of that building. When such advanced computational methods are employed (as they are in this report), the methodology used to determine the optimal envelope design must consider the effects of this interdependence. At the same time, the methodology must be relatively easy to use in the design analysis or the costs of searching for an optimal solution may outweigh the incremental benefits. Ease of computation is especially important in this report because optimal designs are sought for a wide range of climates and energy costs.

The final selection of a methodology must weigh a number of factors. For instance, the most accurate methodology for determining the optimal design configuration for a new building envelope is also the most costly. This "brute force" methodology requires that the total life-cycle costs associated with each possible alternative configuration be calculated. The configuration with the lowest total life-cycle cost is, by definition, the optimal design. While the number of configurations to be considered can be greatly reduced by using good engineering judgment to eliminate improbable designs, this methodology would still require an inordinate amount of computer time and manpower and is therefore unacceptable as a general approach.

A more efficient methodology might be developed which converges on the optimal design configuration. However, this would still require a large number of computer analyses to model adequately the interdependent relationships.

To resolve these difficulties, an alternative approach to design optimization is outlined here which will generally result in the same solution but at considerably less computational expense. This approach concentrates on calculating the incremental contribution of each design modification to the reduction of heating and/or cooling requirements. These modifications are introduced sequentially into the thermal analysis in decreasing order of <u>relative</u> cost effectiveness, along with all the more cost-effective modifications, as follows: First, the heating and cooling requirements of the house without any of the energy conserving modifications are determined. Then the heating and cooling requirements are recalculated as the first, most cost-effective, modification is incorporated into the design and the reduction in those reqirements relative to the base case is calculated. The incremental reduction in space heating and cooling requirements is determined in like fashion for each additional modification, leaving all of the previous (and, by definition, more cost-effective) modifications in the design. As a result, once a given modification has been established as cost effective on an absolute basis, all of the preceding modifications will be cost effective as well.

This methodology will be referred to as the "priority ranking" process. This approach has certain limitations; however, it offers a reasonably accurate methodology for determining the optimal levels of thermal resistance in the envelope components. In addition, the same computer analyses of the heating and cooling requirements, in expanded form to show the contribution of each component to these requirements, can provide much of the information needed to assess the effects of substitutions among components and reorientation of the building.

The priority ranking methodology is a two-step process. In the first step, a trial ordering of modifications, in terms of decreasing relative cost effectiveness, is established, based on good engineering judgment and the results of previous analyses. Computer analyses of the modifications in this trial sequence generally will provide results that are sufficient to rank the modification by relative cost effectiveness. This can be verified when the analysis of this second ordering is completed.[1]

The priority ranking approach is based on several assumptions about the effects of the modifications considered.

(1) Any improvement in the thermal performance of a component will increase the cost of that component within the range of investigation.

(2) The change in the load-reducing potential of any component modification attributable to the overall level of thermal performance of the building envelope will not affect the rank order of the envelope modifications considered. This is because the incremental decision to select any one of several alternative component modifications at any given point is made based on the same envelope configuration at that point.

(3) The interdependence between the overall envelope design and the efficiency of the heating and cooling equipment is irrelevant for the same reason as (2).

(4) Thus, the only type of interdependence that potentially can present a problem in the priority ranking methodology is thermal interdependence, the interdependence among components due primarily to radiation exchange. This occurs because an increase in the thermal performance of one envelope component can increase the heat loss through other components, thereby improving the cost effectiveness of insulation in those other components. Theoretically, this situation could create some instability in the ranking of modifications that are very similar in terms of cost effectiveness. This, however, is not likely to

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[1] In the thermal analysis discussed in section 6, this sequential ordering is based on reductions in heating requirements only in order to facilitate the analysis. As a result, the modifications can be ranked in terms of decreasing energy savings per dollar invested, since the dollar savings are directly proportional to energy savings.

result in a significant problem in identifying the optimal combination of design modifications because this effect on the modifications found to be marginally cost effective is quite small. Moreover, the precise effect of radiation exchange on reductions in heating and cooling loads is difficult to calculate because of shortcomings in the available radiation exchange algorithms. For these reasons, this type of interdependence is not directly considered in the priority ranking methodology.

A final point should be noted: Any attempt to include modifications to the heating and cooling equipment that increase its conversion efficiency in the general priority ordering process is likely to fail. This is because of the high degree of interdependence between the envelope and the equipment operation in terms of energy usage. As the thermal integrity of the envelope is improved, the resulting energy savings from any equipment modification decrease, because the equipment is used less. Similarly, any improvement in the conversion efficiency of the heating or cooling equipment will result in smaller energy savings from any envelope modification. Thus, the priority ranking of envelope and equipment modifications together may indicate that some conservation measures are cost effective which would not be selected in a more careful analysis. In fact, the optimal envelope configuration and optimal equipment design must be determined simultaneously.[1]

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[1] This simultaneous solution to equipment and envelope design is the subject of a forthcoming NBS Interagency Report by the author titled "Simultaneous Economic Optimization of Building Envelope Components and HVAC Equipment Selection at the Design Stage."

4. ENVELOPE CONFIGURATION AND MODIFICATIONS ANALYZED

4.1 PROTOTYPE RANCH HOUSE: DESCRIPTION AND OPERATIONAL ASSUMPTIONS

It is possible to make rough estimates of the thermal performance of individual envelope components and load reductions resulting from modifications to those components using simplistic steady-state heat transfer assumptions. For this type of analysis, it is not necessary to specify the overall building design. However, in order to determine these values using more sophisticated computation methods, the building configuration must be specified in some detail. Moreover, to obtain meaningful data on component performance and load reduction potentials, sensitivity analyses of the most significant energy-related design parameters, such as building size, window areas, and orientation, should be provided. This also requires a detailed description of the building configuration. This section provides a detailed description of the building and its modifications that are analyzed in this report.

The basic building design is a 1200 ft^2, single-family, detached, ranch-style house. This house is shown in figures 4.1 (elevations) and 4.2 (floor plan). It is nearly identical to the "compact, ranch-style" house proposed in a recent NBS publication,[1] as typical of a great deal of new and existing housing in the United States. It is not intended to be a model house that should be copied outright because of its inherent design qualities. Rather, it is intended to serve as a starting point for evaluating envelope design modifications.

The 1200 ft^2 area of this house is smaller than the 1974 national average of 1684 ft^2 for detached houses.[2] However, a one-story house would tend to be smaller than the overall average floor area of all single-family detached houses which includes multistory houses.

Table 4.1 describes the basic envelope component areas for the prototype house. Table 4.2 provides the basic structural details of the various envelope components. Opaque wall construction before and after expansion of the wall thickness is based on 24-in stud centers. In effect, this increases the relative cost of using 2 x 6-in studs instead of 2 x 4-in studs because the increased thickness of the wall framing is not offset by greater spacing between studs. This conservative approach has been taken because in some local building codes 2 x 4-in studs on 24-in centers are permissible.

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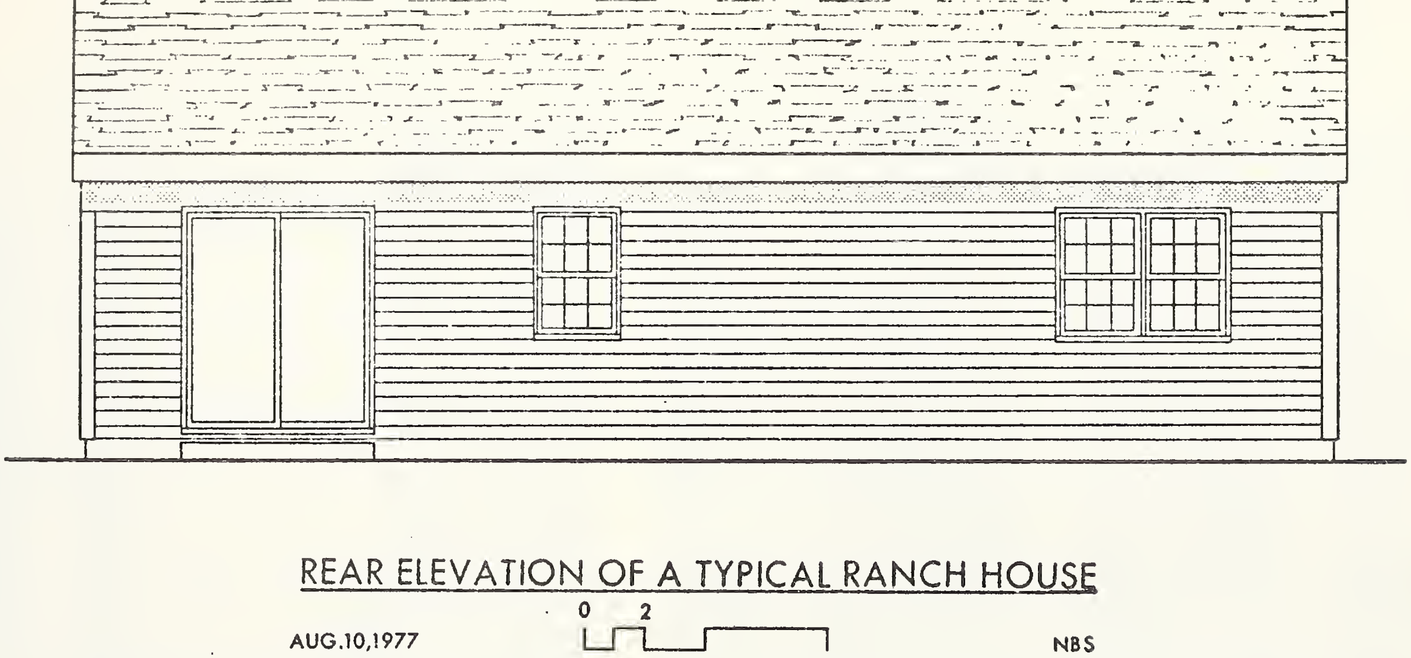
1 S.R. Hastings, Three Proposed Typical House Designs for Energy Conservation Research, NBSIR 77-1309, National Bureau of Standards, Washington, D.C., October 1977.

2 NAHB Research Foundation, "A National Survey of Characteristics and Construction Practices for all Types of One-Family Homes," Rockville, MD, February 1974.



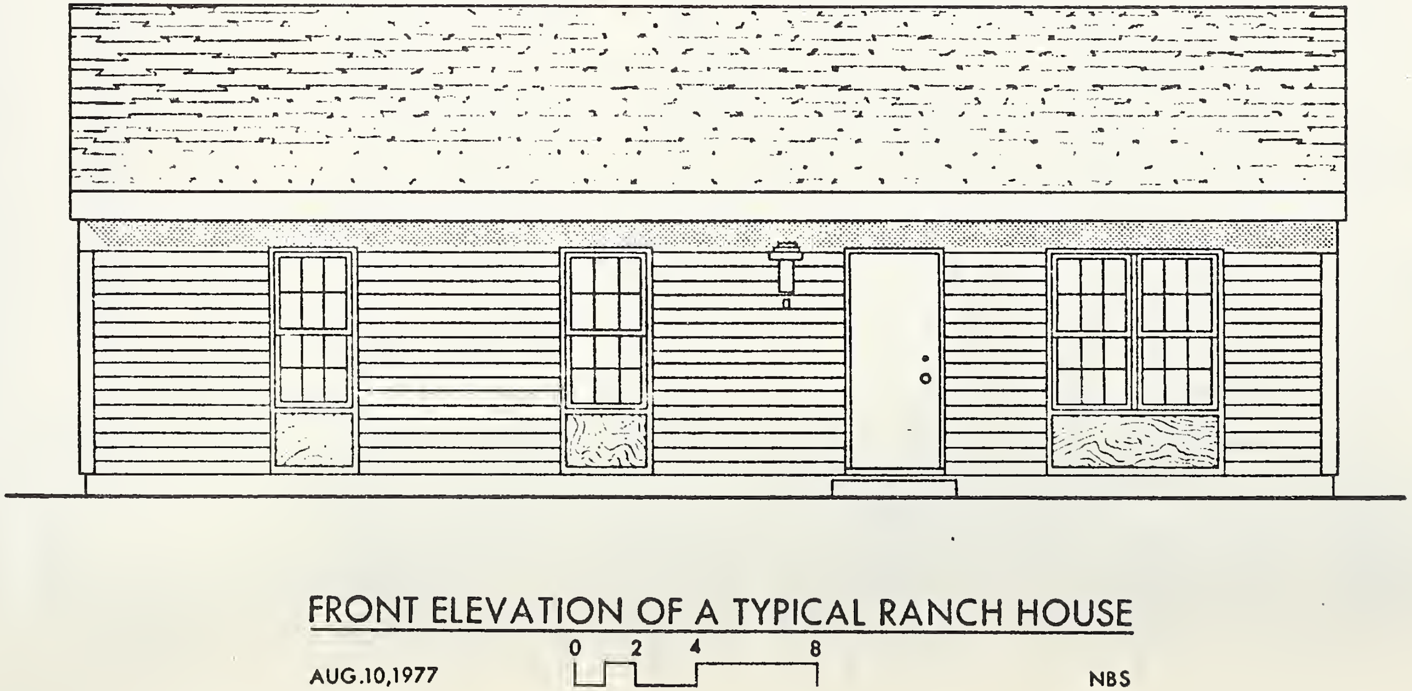


Figure 4.1 Front and rear elevations of prototype ranch house

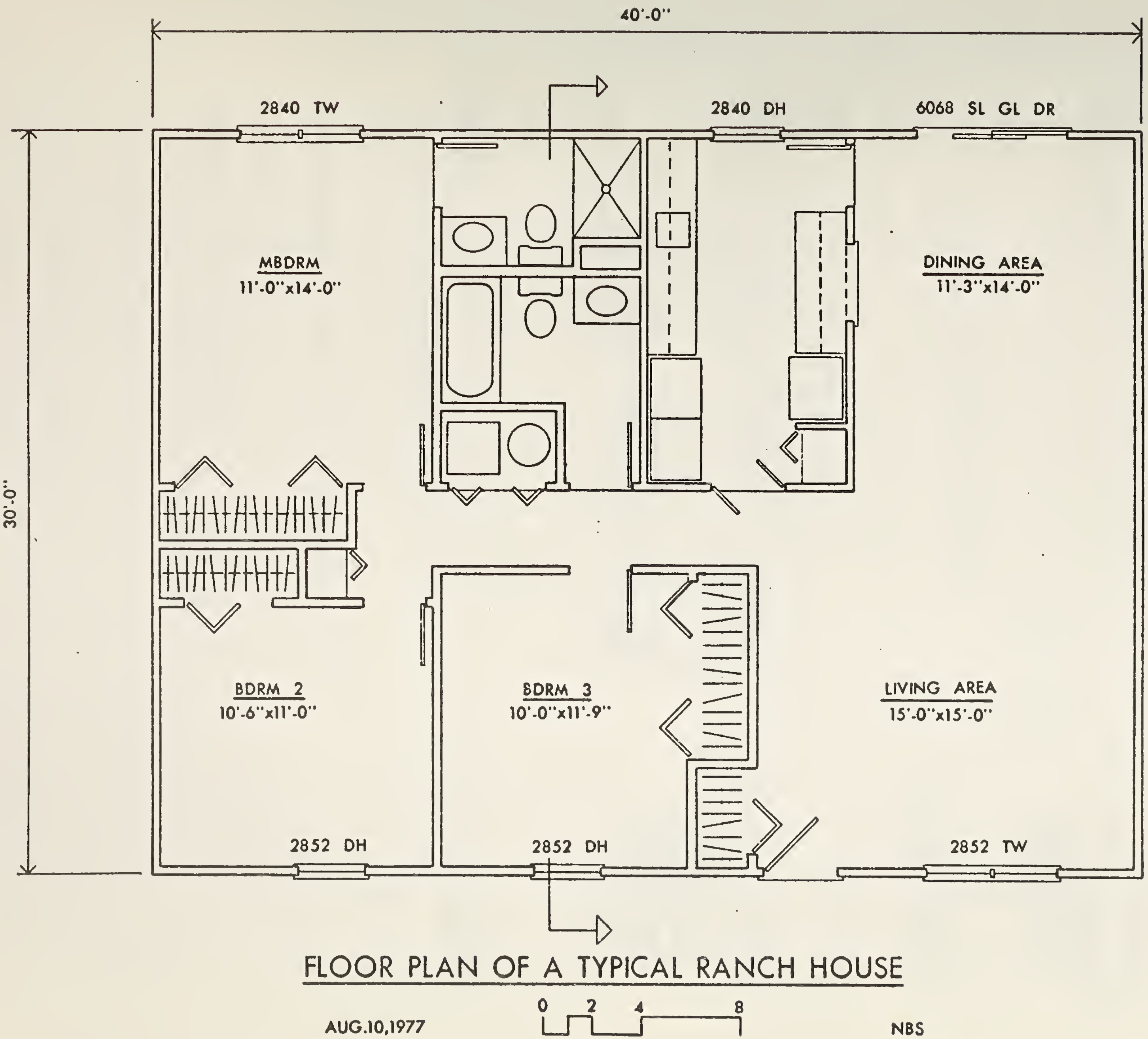


Figure 4.2 Floor plan of prototype ranch house

Table 4.1 Component Areas of 1200 Square-Foot Prototype House

					Area in Ft^2
Ceiling					1200.0
Windows					
North Facing	4 @ 13.8 ft^2				
South Facing	1 @ 20 ft^2				
	1 @ 12 ft^2				
Total					87.1
Sliding Glass Door (South Facing)	1 @ 40 ft^2				40.0
Entry Door					20.0
Opaque Wall Area		Insulated	Stud	Total	
North Facing		181.3 ft^2	63.6 ft^2	244.9 ft^2	
East Facing		209.1 ft^2	30.9 ft^2	240.0 ft^2	
South Facing		189.4 ft^2	58.6 ft^2	248.0 ft^2	
West Facing		209.1 ft^2	30.9 ft^2	240.0 ft^2	
Total		788.9 ft^2	184.0 ft^2	972.9 ft^2	972.9
Floor					1200.0
Total Envelope Area					3520.0

Table 4.2 Basic Construction Details of Prototype House

1. Roof:

   2 x 4-in roof trusses 24-in on center
   1/2-in plywood deck
   building paper
   asphalt shingle roofing

2. Ceiling:

   2 x 4-in ceiling joists, 24-in on center
   1/2-in gypsum wallboard

3. Exterior wall:

   3/8-in wood siding
   1/2-in fiberboard sheathing, regular density
   2 x 4-in studs, 24-in on center
   polyethylene vapor barrier (4 mil)
   1/2-in gypsum wallboard

4. Floor:

   2 x 10-in floor joists, 24-in on center
   3/4-in wood subfloor
   5/8-in plywood floor
   pad
   carpet

5. Windows:

   Premium quality wood double hung or slider

6. Exterior Entry Door:

   Premium quality wood, 1-1/2-in thick (U = 0.49)

7. Sliding Glass Door:

   Premium quality, wood frame

The glass-to-gross-wall area ratio is 11.4 percent. This ratio approaches the minimum desirable glass area for the room area considered.[1] The prototype house has larger windows on the south face of the building, and the house is oriented so that the longer walls face north and south. Windows have been excluded from the side elevations.[2] This is a common practice if neighboring houses are close and a lateral view is undesirable.[3] This orientation of the building and the south-facing glass will be shown to be advantageous in section 6. The effects of alternative orientations for wall elevations and glass area will be examined as well in that section.

Although figure 4.2 provides the floor plan of this prototype house, it is somewhat limited in usefulness because only the outside walls can be modeled in the NBSLD computer program.[4] This shortcoming has several effects on the analysis:

(1) the mass storage effect of the internal partitions is ignored,

(2) the modeling of radiation exchange among the interior envelope surfaces is distorted,

(3) solar radiation transmitted through the windows must fall entirely upon the interior envelope surfaces (i.e., floor, ceiling, and outside walls) rather than upon interior partition surfaces, and

(4) thermal zoning of the rooms cannot be modeled.

The resulting effects on calculating heating and cooling requirements will be discussed further in section 5.

Air infiltration rates are calculated in terms of air changes per hour and thus are not directly associated with specific sources of leakage, such as windows and doors. The air change rates used are based upon an empirical relationship demonstrated by Achenbach and Coblentz in a number of electrically heated houses.[5]

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[1] S.R. Hastings, Three Proposed Typical House Designs.

[2] Note that all rooms (except bathrooms) have windows large enough for emergency egress.

[3] S.R. Hastings, Three Proposed Typical House Designs.

[4] Efforts are currently underway to resolve the problem of internal partitions and thermal zoning in the NBSLD computer program. This is a difficult problem, however, since it requires running the load analysis program simultaneously for each room and "coupling" the resulting loads.

[5] P.R. Achenbach and C.W. Coblentz, "Field Measurements of Air Infiltration in Ten Electrically Heated Houses," ASHRAE Transactions Vol. 69, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, pp. 358-365, 1963.

This relationship determines air changes per hour (AC) as a function of wind speed (V) in miles per hour and inside-outside temperature differentials (ΔT) in °F. This relationship, adapted for use in this report, is represented by the equation

$$AC = 1.68 \ (0.15 + 0.013 \ V + 0.005 \ \Delta T). \qquad (4\text{-}1)$$

The relationship is depicted graphically in figure 4.3 for a range of wind speeds and temperature differentials. Note that the equation results in an air change rate of approximately 1.0 at a 15 MPH wind speed and a ΔT of 50°F, but considerably less under more typical conditions. For example, at a 7.5 MPH wind speed and a temperature differential of 25°F, the hourly air change rate is approximately 0.63. The minimum rate of hourly air change allowed is 0.25. The air change rate measured in the NBS Bowman House study[1] after the house was caulked, weatherstripped, fully insulated, and fitted with storm windows was 1.0 when the ΔT was 50°F and wind speed was 15 MPH.

Lower air change rates have been measured in other houses under controlled conditions.[2] However, such conditions do not generally include the effects of such considerations as door openings and controlled ventilation of kitchens and bathrooms. Thus, the infiltration rates based on equation (4-1) appear reasonable for actual occupancy. It would be highly desirable to evaluate the effectiveness of certain envelope modifications in reducing the rate of air infiltration; however, at present such data are not available. Therefore, this report does not consider the increased use of sealants and tighter fitting doors and windows.

Operational considerations have a significant effect on heating and cooling loads and therefore must be specified. The following assumptions were made in the computer analysis:

(1) Two adults and two children occupy the house year-round. Daily heat release profiles for the occupants are shown in table 4.3 along with heat release from lighting and equipment operation (including cooking, bathing, dishwashing, refrigeration, etc.). Because of limitations in the NBSLD computer program, these are assumed to be the same in both summer and winter. These internal heat releases are shown graphically in figure 4.4.

(2) During heating periods thermostat settings are assumed to be 68°F between 7 a.m. and 11 p.m., with setback to 60°F between 11 p.m. and 7 a.m. During cooling periods the thermostat setting is 78°F. No heating or cooling is required when the indoor temperature floats between 68°F (60°F setback) and 78°F.

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[1] D.M. Burch and C.M. Hunt, Retrofitting an Existing Wood-Frame Residence Energy Conservation--An Experimental Study, NBSIR 77-1274, National Bureau of Standards, Washington, D.C., 1977.

[2] P.R. Achenbach and C.W. Coblentz, "Field Measurements of Air Infiltration."

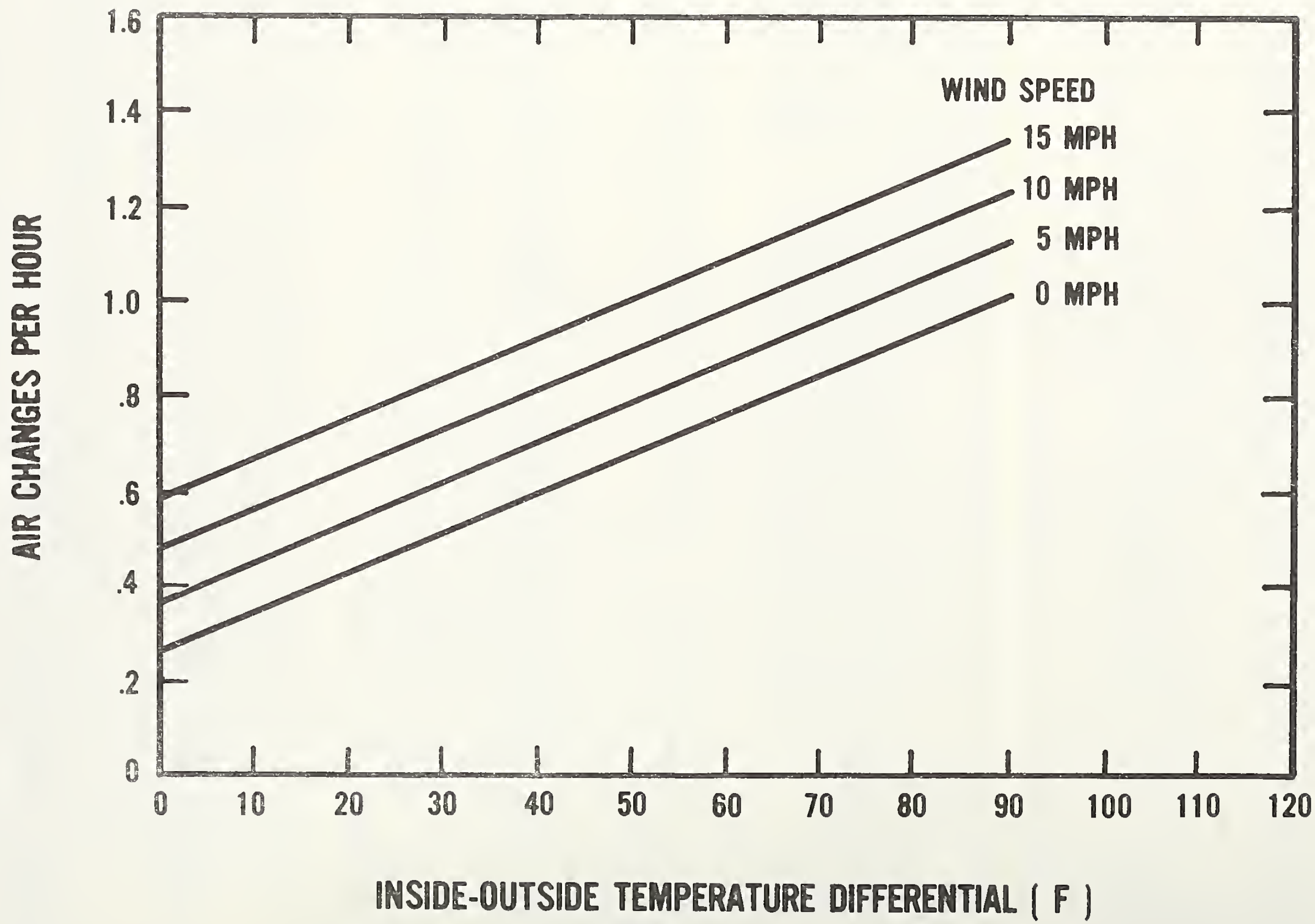

Figure 4.3 Infiltration rate schedule (air changes per hour)

Table 4.3 Hourly Lighting, Equipment, and Occupant Heat Release Schedule (Btu/hr, 1200 Ft^2 House)

Hour	Lights	Equipment	Occupant Sensible	Occupant Latent
1	0	717	1050	150
2	0	717	1050	150
3	0	717	1050	150
4	0	717	1050	150
5	0	717	1050	150
6	0	2025	1050	150
7	2130	2995	1050	150
8	2130	4008	960	240
9	49	2405	384	96
10	49	2574	384	96
11	49	2405	384	96
12	49	3712	384	96
13	49	2616	384	96
14	49	2025	384	96
15	49	2025	384	96
16	49	2151	662	166
17	49	2025	662	166
18	49	2742	960	240
19	1065	2953	960	240
20	1065	3417	960	240
21	2130	4219	960	240
22	2130	2616	960	240
23	2130	2953	960	240
24	2130	2025	1050	150

Source: U.S. Department of Housing and Urban Development, Residential Energy Consumption, Single-Family Housing, Report No. HUD-HA1-2 (Prepared by Hittman Associates, Columbia, Md.), Washington, D.C., 1973.

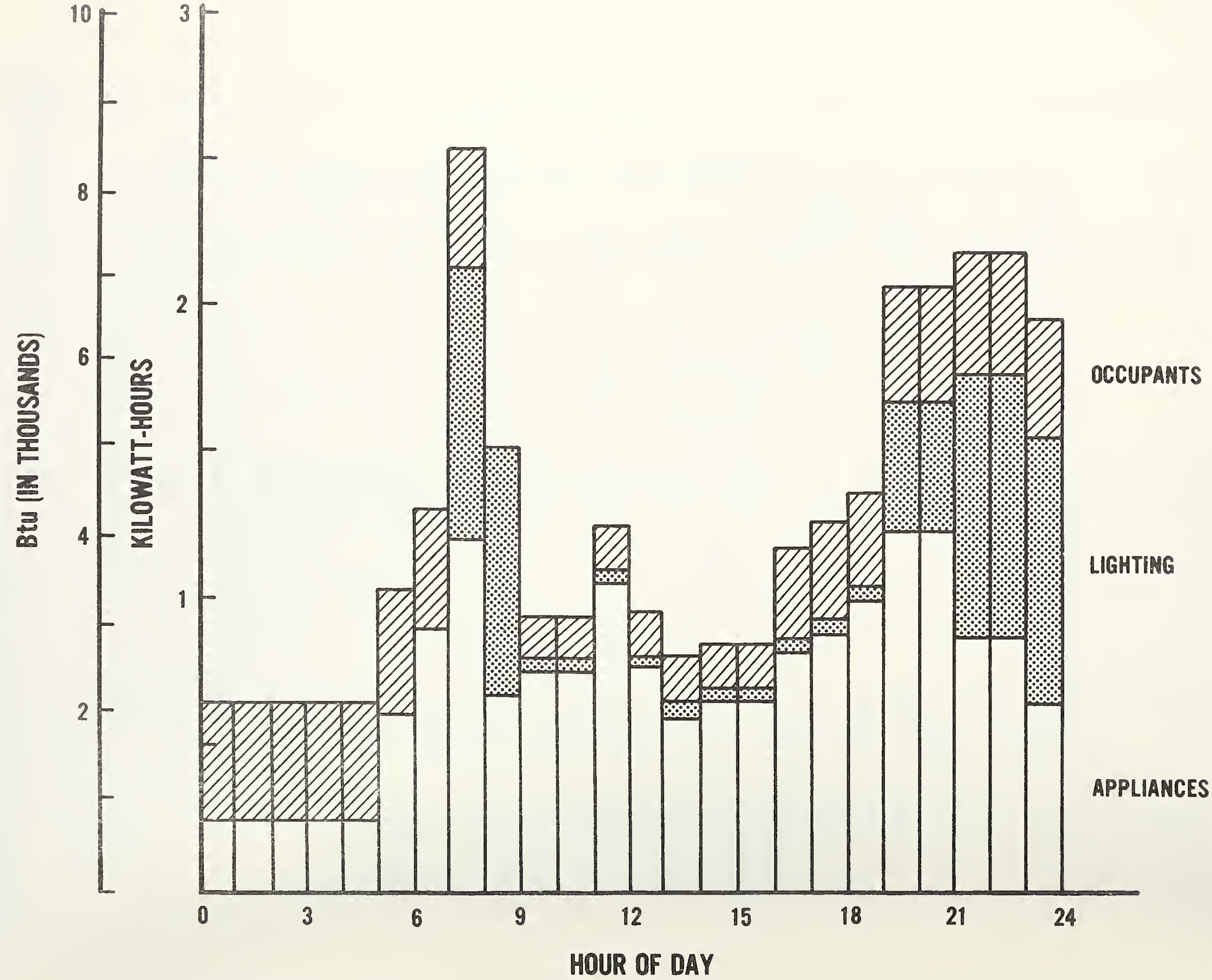

Figure 4.4 Hourly internal loads assumed in the prototype house simulation

(3) Windows and doors are assumed to be closed whenever the house is being heated or cooled. Natural ventilation, or a whole-house fan, is assumed to be used instead of mechanical air conditioning whenever the outdoor temperature is below 78°F. While this may not be typical operating procedure for many homeowners, this assumption is made because (a) it is consistent with energy-conserving operating procedures; and (b) the point at which windows are closed and the air conditioners turned on will vary widely depending on the individual homeowner's perception of comfort. As a result, the potential negative effects of insulation on cooling loads, which can occur when the outdoor temperature is below the indoor temperature, are avoided. If windows and doors are always kept shut, it is likely that increased wall insulation levels and multiple glazing will increase, rather than decrease, overall cooling requirements.

This study does not model the opening of windows to reduce indoor temperatures below 78°F at night or early morning with the subsequent closing of windows in anticipation of offsetting later air conditioning requirements. However, indoor temperatures are allowed to float as high as 78° during heating periods before windows are opened enough to offset potential air conditioning loads. This buffer can alleviate potential heating loads as outdoor temperatures begin to fall.

4.2 DESIGN MODIFICATIONS TO REDUCE SPACE HEATING AND COOLING REQUIREMENTS

This section outlines and discusses the design options evaluated in this study. Only options which can be modeled satisfactorily with the NBSLD computer program were evaluated.

4.2.1 Building Shape and Orientation

Building shape and orientation can have a significant impact on energy use because of the influence of solar and wind loads. Since NBSLD is not sensitive to wind direction, this study examines orientation only with respect to solar loads. This report also restricts its analysis of orientation effects to the four major compass points. Relative heat losses and gains through the four wall elevations are calculated over the actual load hours encountered. The change in sensitivity to orientation as the building becomes better insulated also is examined.

4.2.2 Window Orientation and Sizing

Under certain conditions windows can help offset both heating and cooling loads. For example, properly managed south-facing windows can sometimes result in a net reduction in annual heating loads. Similarly, by opening windows to permit cross ventilation, air conditioning loads can be reduced (provided, of course, that the outdoor temperature and air quality are acceptable).

In this study, solar heat gains through windows are calculated only for the north and south elevations since there are no windows on the ends of the house. During the warmer months (May through September) solar gains through all windows are assumed to be reduced by 50 percent due to shading by exterior or interior means. Solar gain data are provided to adjust for further shading of south-facing windows.

The effects of cross ventilation during those periods when it will eliminate potential air conditioning loads are considered. However, the effects of window size and orientation on the maximum possible rate of natural ventilation are not considered due to modeling limitations.

4.2.3 Insulation

Table 4.4 shows the alternative insulation resistances in the attic, interior walls, and floor of the prototype house, as well as three levels of window glazing that are examined in this study. Table 4.4 also provides the resulting U-values of the various envelope components affected.

The analysis assumes that the insulation is installed evenly throughout the attic; in actual practice, however, higher insulation levels cannot be installed in perimeter areas where the roof is too close to the attic floor. In general, raising the roof line to accommodate higher insulation levels in these areas cannot be justified economically, unless a substantial roof overhang is desired.

Structural modifications to the exterior walls are considered only to accommodate greater insulation thicknesses than are possible with ordinary construction. R-11 and R-13 insulation batts are assumed to fit between conventional 2 x 4-in framing in exterior walls without compression. In order to accommodate R-19 insulation batts (approximately 6 inches thick) into the exterior wall, 2 x 6-in framing is used. However, since the actual thickness of a 2 x 6-in stud is approximately 5.5 inches, the R-19 batt must be slightly compressed, reducing its resistance to R-18.[1]

An alternative approach to increase the thermal performance of exterior walls beyond R-13 is the use of extruded polystyrene sheathing in place of more commonly used fiberboard. Polystyrene sheathing is available in several thicknesses, ranging from 0.75 inches to 2.0 inches. Because this sheathing covers the entire opaque wall area, it greatly reduces the thermal bridging effect of the studs in the wall construction. However, because of its poor structural performance, use of this material generally requires some corner bracing, and in actual practice, plywood sheathing is often substituted at the corners of the house, reducing the overall applicability of the polystyrene sheathing.

The costs and steady-state U-values used in this report for the 2 x 6-in, 24-in on center wall with R-19 glass fiber batts and the 2 x 4-in, 24-in on center

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[1] Private communication with Owens Corning Fiberglas representative, Granville, Ohio.

Table 4.4 Alternative Component Designs and Corresponding U-Values (Winter Design)

Attic

Nominal Resistance	U
R-0	0.5720
R-11	0.0844
R-19	0.0498
R-30	0.0321
R-38	0.0255
R-49	0.0200

Walls

Nominal Resistance	U
R-0	0.2180
R-11	0.0824
R-13	0.0756
R-19[a]	0.0577
R-23[b]	0.0467

Floors

Nominal Resistance	U
R-0	0.2324
R-11	0.0675
R-19	0.0466

Windows

Description	U
Single Pane	1.13
Storm Window Over Single Pane	0.56
Storm Window Over Double Pane	0.36

Door

Description	U
Prime Door	0.49
Prime Door Plus Storm Door	0.33

Sliding Glass Door

Description	U
Single Pane	1.13
Double Pane	0.58

[a] Nominal 2 x 6-in studs provide 5.5-in cavity. R-19 glass fiber batt in 5.5-in cavity compresses to R-18.

[b] R-5 polystyrene sheathing is substituted for R-1.32 fiberboard sheathing.

wall with R-13 glass fiber batts and R-5 (1-in) polystyrene sheathing are nearly identical, although such costs may vary over time and in different locations. Both systems are gaining increasing acceptance in the building community with builders showing preference for one or the other based largely on their personal experience. The 2 x 6-in stud wall tends to decrease the amount of available floor space slightly. This can generally be compensated for by increasing the outside dimensions of the house at relatively small cost.[1] The 2 x 4-in, 24-in on center wall with polystyrene sheathing might be considered unacceptable from a structural integrity standpoint and thus the 2 x 4-in, 16-in on center wall is more likely to be used, offsetting its cost advantage over the 2 x 6-in, 24-in on center wall. Thus, the 2 x 6-in, 24-in on center stud wall with R-19 insulation batts is used for thermal analysis of the envelope. However, because both systems have relatively small mass and the same U-value, the thermal performance of either wall is nearly identical.

In order to increase the thermal resistance of the wall beyond this level, R-5 polystyrene sheathing is used in conjunction with the 2 x 6-in frame walls, giving an overall U-value of approximately 0.047. The derivation of the steady-state U-values for each wall system analyzed in this report is shown in table 4.5.

4.2.4 Multiple Glazing

Multiple glazing is used to decrease thermal transmission losses through the windows. Because storm windows have slightly better thermal performance characteristics (U = 0.56 versus U = 0.58 to 0.69) and somewhat lower cost than double-pane windows ($225 versus $255 for this house), they are used to provide double glazing. (Superior infiltration abatement characteristics of storm windows are not considered in this study but are likely to make them even more cost effective.) In order to provide triple glazing, double-pane windows are used in conjunction with storm windows. In all cases, tight-fitting, self-storing (triple track), metal-frame storm windows are assumed. No adjustment for prime window sash is made as the windows are sized by glass area. Solar transmission through single glazing is assumed to be 80 percent; through double and triple glazing it is assumed to be 70 percent and 60 percent, respectively.

4.2.5 Doors

A tight-fitting, metal and glass storm door is used to reduce heat transmission through the front door of the house. In actual practice it would be better to replace the glass inserts in the storm door with screen inserts during the non-heating months. However, in the NBSLD analysis the glass inserts must be modeled throughout the year. Infiltration abatement characteristics were not considered since it is assumed that the prime door is tight fitting.

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[1] For the 1200 ft^2 ranch house, this would require that the length of the house be expanded by approximately 0.75 ft at a cost (including foundation, flooring, wall, and roof) of approximately $100 (1979 dollars). Note that this has no effect on the cost of inside construction since the inside area is unchanged.

Table 4.5 Alternative Wall Construction Methods to Increase Insulation Above R-11

	Thermal Resistance (R-values) of Wall Components ($ft^2 \cdot h \cdot °F/Btu$)			Thermal Transmittance (U-values) of Wall Cross Sections ($Btu/ft^2 \cdot h \cdot °F$)			Cost/ft^2 Above R-11 (1979 $)
Cavity Insulation	Stud	Sheathing	Wallboard Siding, Air Surfaces	Cavity	Stud	Weighted[a]	
11	4.17 (2 x 4-in)	1.32 (Fiberboard)	1.94	0.070	0.135	0.083	-
13	4.17 (2 x 4-in)	1.32 (Fiberboard)	1.94	0.062	0.135	0.077	$0.0625
19	6.55 (2 x 6-in)	1.32 (Fiberboard)	1.94	0.047	0.102	0.058	$0.32[b]
13	4.17 (2 x 4-in)	5.0 (Polystyrene)	1.94	0.050	0.090	0.058	$0.32[c]
19	6.55 (2 x 6-in)	5.0 (Polystyrene)	1.94	0.040	0.074	0.047	$0.58

[a] Cavity area = 80%; stud area = 20% (This may vary somewhat from house to house and wall to wall.)

[b] Does not include adjustment for decreased inside area.

[c] Does not include adjustment for change from 24-in centers to 16-in centers (most conventional construction would begin with 16-in centers).

The south-facing sliding glass door is upgraded by replacement with a double-glazed door having a 1/2-in air space.

4.2.6 Modification Cost Data

Table 4.6 lists the costs of the modifications outlined in table 4.5. They are based on data gathered in 1977 by the NAHB Research Foundation in a report contract to NBS entitled "Selected Cost Data on Residential Construction." These data include overhead and profit factors and were adjusted to end-year 1979 dollars using a 30 percent cost inflation factor.[1] Regional variations may be appropriate, although these are generally less than 10 percent. Recent investigation reveals that the incremental cost of premium quality double-glazed windows and doors are often below the costs used in this report, due to greatly increased production quantities in recent years. However, no adjustment was made to account for seal failure between glazings, which would require replacement in some cases, resulting in increased life-cycle costs. Storm doors will generally not last as long as the other modifications considered. Thus one replacement storm door has been factored into the storm door cost shown in table 4.6. A real discount rate of zero percent was used to discount the future replacement cost ($75) in current dollars to present value so that the year of replacement does not become critical to the analysis.

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[1] This factor represents inflation in the residential construction industry from mid-1977 to end-year 1979, and is based on the Boeckh and Engineering News-Record construction cost indexes. See U.S. Department of Commerce, "Construction Review," Vol. 26, No. 1, January 1980.

Table 4.6 Envelope Modification Costs (1979)[a]

	Total Cost		Incremental cost	
	Total Area	Square Foot	Total Area	Square Foot
1. Attic Insulation (1200 ft^2 gross)				
R-11	$235	$0.20	$235	$0.20
R-19	345	0.29	110	0.09
R-30	515	0.43	170	0.14
R-38	625	0.52	110	0.09
R-49	795	0.66	170	0.14
2. Wall Insulation (1120 ft^2 gross)[b]				
R-11	220	0.23	220	0.23
R-13	290	0.30	70	0.07
R-19	580	0.60	290	0.30
R-23	870	0.90	290	0.30
3. Floor Insulation (1200 ft^2 gross)				
R-11	280	0.23	280	0.23
R-19	405	0.34	125	0.11
4. Windows (87.1 ft^2)				
Storm Windows	225	2.58	225	2.58
Storm Windows and double pane glass (relative to single pane)	480	5.51	255	2.93
5. Sliding Glass Door (40 ft^2)				
Double Pane Glass (relative to single pane)	180	4.50	180	4.50
6. Door (20 ft^2)				
Storm Door	150[c]	7.50	150	7.50

[a] Installed costs in new housing, including overhead and profit. Source: NAHB Research Foundation contract report, "Selected Cost Data on Residential Construction," 1977 updated to end-year 1979 costs using a cost adjustment factor of 30 percent. (Adjustment factor based on construction cost indexes for residential construction (Boeckh and Engineering News-Record).)

[b] Costs for wall insulation are based on gross wall area of 1120 ft^2 rather than a net wall area of 973 ft^2. Cost per square foot of actual net wall area is therefore higher than nominal cost.

[c] Storm door cost includes initial cost of $75 plus one replacement door at $75.

5. LOAD-ESTIMATING METHODOLOGY

Section 6 provides the actual analysis of the prototype ranch house and component modifications described in the preceding chapter. An expanded output version[1] of the NBS Load Determination[2] (NBSLD) program, was used to carry out this analysis. The reasons for using this modified program and the assumptions made are described in this chapter.

It has been well established that life-cycle cost analysis can play an important role in designing a building that has reduced energy requirements over the long run. The usefulness of such an analysis is limited largely by the availability of accurate thermal engineering data that relates the sensitivity of long-term heating and cooling requirements to changes in design parameters. For this analysis, it is especially important that the incremental reduction in energy requirements resulting from design modifications be reasonably accurate in absolute terms. This is because life-cycle costs can only be reduced through design modifications which have incremental benefits (in terms of reduced present-value energy expenditures) greater than incremental costs.

Under ideal circumstances, actual measured energy data would be preferred to estimate the life-cycle costs of alternative building designs in different climates. In practice, however, it is nearly impossible to use actual measurements for the following reasons:

(1) Operational factors, such as window and door openings, thermostat settings, internal heat release, solar gain, etc., are likely to be different from building to building.

(2) Identical houses in identical surroundings that are located in different climatic zones are not likely to be found in order to determine the effects of climate on building energy requirements.

(3) Climate patterns during different measurement periods may not be comparable.

(4) It is impractical to measure the individual effects of a wide range of different conservation features, used in different combinations, in different climates, and under different operational modes.

To avoid these problems, a load determination model is used which holds all variables constant except those being analyzed. Such a model can be used to evaluate heating and cooling loads in different climates under a range of design and operational assumptions. However, steady-state load determination models do not adequately estimate design or annual heating and cooling

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[1] S. R. Petersen and J. P. Barnett, Expanded NBSLD Output for Analysis of Thermal Performance of Building Envelope Components, NBSIR 80-2076, National Bureau of Standards, Washington, D.C., 1980.

[2] T. Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads.

requirements, especially if the annual requirements are based on heating and cooling degree days (base 65°F). For this reason, a load determination model that calculates the dynamic thermal response of a house and considers solar gains, internal loads, air infiltration rates, and hour-by-hour weather data typical of a given geographic location is needed. NBSLD, which meets all of these requirements, was selected to provide the necessary heating and cooling load data used in this report.

NBSLD was developed originally as a research tool to calculate accurately heating and cooling loads in buildings. To meet the requirements of this study, the program had to be modified because NBSLD in its original format provided only total heating and cooling loads.

To better understand the effects of each of the building envelope components on annual heating and cooling requirements, the actual sources of the heating and cooling loads also had to be identified. This load source analysis allows the designer to determine the extent to which heating and cooling loads are influenced by heat gains and losses through ceilings, walls, floors, windows, doors, and infiltration, as well as the effects of solar gains and internally generated heat. The effect of building orientation can be quantified directly by observing the performance of the similar envelope components at different compass orientations, without rotating the building. The mechanisms by which the various envelope components lose or gain heat during actual heating and cooling periods can be better understood and quantified as the design is modified.

A printout of the expanded NBSLD output format (NBSLD-XO) with data for the prototype single-family house, based on the Washington, D.C., Test Reference Year (TRY) weather tape, is shown in table 5.1. This 1200 ft^2 house is fitted with R-19 attic insulation, R-11 wall insulation, R-11 floor insulation, and storm windows. The columns above the component titles contain (1) an internal identification number, (2) the compass orientation, where appropriate (0° = north), (3) the winter design U-value, and (4) the component area, in square feet, where appropriate. The sources of monthly and annual heating requirements (H and TH) are shown first, followed by the sources of monthly and annual cooling requirements (C and TC), all in Btu. Positive numbers are heat gains; negative numbers are heat losses. Note that cooling requirements and their sources are divided into two parts: (1) cooling requirements where the outdoor temperature is greater than the indoor temperature (C+ and TC+) and those where the outdoor temperature is less than the indoor temperature (C- and TC-).[1] The final part of this NBSLD-XO output contains a summary of monthly and annual heating and cooling hours, design heating and cooling loads, and total annual heating and cooling requirements.

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[1] Cooling requirements for hours with outdoor temperatures below indoor temperatures are not examined in this report as it is assumed that increased ventilation is generally sufficient to satisfy occupant comfort criteria during these periods.

Table 5.1 Sample Output from NBSLD-XO

INSIDE SURFACE FLUXES,INTERNAL & AIR INFILTRATION LOADS

	1.0000	2.0000	2.0000	3.0000	3.0000	3.0000	3.0000	2.0000	2.0000
	.0000	.0000	.0000	.0000	.0000	.0000	.0000	90.0000	90.0000
	.0498	.0701	.1349	.5600	.5600	1.1300	1.1300	.0701	.1349
	1200.0000	189.4000	58.6000	32.0000	32.0000	40.0000	40.0000	209.0600	30.9400
	CEILNG	SOUTH INSUL WALL	SOUTH STUD WALL	SOUTH CD/CV WINDOW	SOUTH SOLAR WINDOW	SOUTH CD/CV WINDOW	SOUTH SOLAR WINDOW	WEST INSUL WALL	WEST STUD WALL
1 H	.1192308+07	.2397375+06	.1379448+06	.3901900+06	-.4488656+06	.9438471+06	-.6412366+06	.3056296+06	.8505526+05
2 H	.7390958+06	.1513270+06	.7804689+05	.2481491+06	-.2952313+06	.6036591+06	-.4217590+06	.1856956+06	.4753836+05
3 H	.5979127+06	.1318406+06	.6104029+05	.2089340+06	-.2285363+06	.5151519+06	-.3264804+06	.1528797+06	.3592548+05
4 H	.2233349+06	.6027621+05	.2530057+05	.8348641+05	-.6593485+05	.2092779+06	-.9419264+05	.6348980+05	.1265890+05
5 H	.3523096+05	.1298946+05	.4494588+04	.1633483+05	-.8162717+04	.4112665+05	-.1166102+05	.1401877+05	.1989128+04
6 H	.2032954+04	.7063840+03	.3552468+03	.9056908+03	-.2467295+03	.2349522+04	-.3524707+03	.5941447+03	.1780932+03
7 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
8 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
9 H	.2025263+05	.6784084+04	.2135392+04	.7082957+04	-.3664821+04	.1770643+05	-.5235458+04	.7766317+04	.1060973+04
10 H	.2402957+06	.5553307+05	.1943746+05	.7316912+05	-.7775714+05	.1801647+06	-.1110816+06	.6439698+05	.1108043+05
11 H	.4395996+06	.8642027+05	.3205164+05	.1343144+06	-.1416140+06	.3257528+06	-.2023057+06	.1055423+06	.2196499+05
12 H	.8423710+06	.1678687+06	.8578859+05	.2719301+06	-.3243626+06	.6725325+06	-.4633751+06	.2105179+06	.5489853+05
TH	.4332434+07	.9134833+06	.4465955+06	.1434496+07	-.1594376+07	.3511569+07	-.2277680+07	.1110531+07	.2723501+06
1C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
1C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
4C+	-.6544206+05	-.1475578+05	-.2285909+04	-.1590434+04	-.8155196+05	-.2750533+04	-.1165028+06	-.1519746+05	.9567864+02
4C-	-.1314134+05	-.2531284+04	.9505265+02	.1711702+04	-.2530892+05	.4531562+04	-.3615560+05	-.3320925+04	.3126089+03
5C+	-.1315742+06	-.2148369+05	-.2318625+04	-.5386793+04	-.5734580+05	-.1229949+05	-.8192258+05	-.2733340+05	-.9082086+02
5C-	-.2564684+05	-.2719960+04	.7699556+03	.1781815+04	-.1312156+05	.4743151+04	-.1874508+05	-.4065274+04	.5171973+03
6C+	-.3354667+06	-.4690426+05	-.1718595+05	-.2054435+05	-.9101327+05	-.4620030+05	-.1300190+06	-.6623420+05	-.1089552+05
6C-	-.7490011+04	.8836756+03	-.4382277+03	.2536591+04	-.5469760+04	.6683244+04	-.7813942+04	-.1008917+04	-.8769797+03
7C+	-.4022830+06	-.6106322+05	-.2216429+05	-.2749085+05	-.1197850+06	-.6235138+05	-.1711214+06	-.8805261+05	-.1433497+05
7C-	-.2308930+05	.3137188+03	.5726293+01	.3844192+04	-.1197515+05	.9983401+04	-.1710735+05	.8053635+02	-.8054077+03
8C+	-.2772188+06	-.5472660+05	-.1795536+05	-.1413301+05	-.1291840+06	-.3090094+05	-.1845486+06	-.6374201+05	-.6932955+04
[illegible]	-.3023394+05	-.2930918+04	.2787151+02	.3498333+04	-.2205696+05	.9243873+04	-.3150995+05	-.1703510+04	-.1679988+02
[illegible]	-.1009482+06	-.3116220+05	-.9809356+04	-.6184978+04	-.1000118+06	-.1370012+05	-.1428740+06	-.2520676+05	-.1772849+04
[illegible]	-.2745304+05	-.6597524+04	-.1013777+04	.3017367+04	-.2817442+05	.7948957+04	-.4024917+05	-.2564289+04	.4950665+03
[illegible]	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
10C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
TC	-.1447987+07	-.2436780+06	-.7227288+05	-.5894042+05	-.6849986+06	-.1250686+06	-.9785695+06	-.2993488+06	-.3430575+05
TC+	-.1320933+07	-.2300958+06	-.7171949+05	-.7533041+05	-.5788919+06	-.1682028+06	-.8269884+06	-.2867664+06	-.3393143+05
TC-	-.1270545+06	-.1358229+05	-.5533992+03	.1639000+05	-.1061068+06	.4313419+05	-.1515811+06	-.1258238+05	-.3743146+03

INSIDE SURFACE FLUXES, INTERNAL & AIR INFILTRATION LOADS

	4.0000	2.0000	2.0000	3.0000	3.0000	2.0000	2.0000	8.0000	.0000
	180.0000	180.0000	180.0000	180.0000	180.0000	-90.0000	-90.0000	.0000	.0000
	.4900	.0701	.1349	.5600	.5600	.0701	.1349	.0675	.0000
	20.0000	181.3000	63.6000	55.1000	55.1000	209.0600	30.9400	1200.0000	.0000
	NORTH	NORTH INSUL	NORTH STUD	NORTH CD/CV	NORTH SOLAR	EAST INSUL	EAST STUD	SOUTH CRL SP	
	DOOR	WALL	WALL	WINDOW	WINDOW	WALL	WALL	FLOOR	LIGHTS
1 H	.2112830+06	.2827592+06	.1868828+06	.6706412+06	-.6321888+05	.3046664+06	.8480957+05	.1079258+07	-.3939428+06
2 H	.1336393+06	.1784413+06	.1125277+06	.4265035+06	-.5465013+05	.1865091+06	.4985936+05	.7819390+06	-.3142237+06
3 H	.1114964+06	.1490644+06	.8741253+05	.3590476+06	-.6939551+05	.1483831+06	.3752359+05	.5901146+06	-.2929501+06
4 H	.4366441+05	.6249205+05	.3286610+05	.1434285+06	-.4439963+05	.6049279+05	.1412475+05	.2302806+06	-.1394982+06
5 H	.7632054+04	.1280702+05	.5405979+04	.2805533+05	-.1133933+05	.1039421+05	.2135683+04	.3835286+05	-.3089360+05
6 H	.4246215+03	.6613988+03	.4217799+03	.1555249+04	-.7482705+03	.6738631+03	.1781226+03	.5176440+03	-.2276662+04
7 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
8 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
9 H	.3711361+04	.6789028+04	.2582331+04	.1216741+05	-.1778415+04	.6592479+04	.1166867+04	.3144531+04	-.1525087+05
10 H	.3923295+05	.5896430+05	.2715272+05	.1257270+06	-.2006781+05	.6003334+05	.1203531+05	.9334473+05	-.1405503+06
11 H	.7262855+05	.9828118+05	.5262776+05	.2308530+06	-.2290200+05	.1031975+06	.2312961+05	.2128539+06	-.2131457+06
12 H	.1471403+06	.1946651+06	.1234032+06	.4673321+06	-.4380968+05	.2094112+06	.5590254+05	.8436186+06	-.3495236+06
TH	.7708529+06	.1044925+07	.6312829+06	.2465311+07	-.3323096+06	.1090354+07	.2808654+06	.3873424+07	-.1892256+07
1C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
1C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
4C+	-.2962643+04	-.4039750+04	.2722191+04	-.2691968+04	-.4070866+05	-.1133062+05	-.1557668+04	.7362244+05	-.8789319+04
4C-	.2818149+03	.4943629+03	.1744388+04	.2952322+04	-.1320196+05	-.1036391+04	.2278747+03	.2631212+05	-.7172870+04
5C+	-.7725407+04	-.9781129+04	.3039115+04	-.9217511+04	-.5085371+05	-.1954225+05	-.3684650+04	.1297879+06	-.2411472+05
5C-	-.2600901+03	-.2536488+03	.2097532+04	.3067835+04	-.1201476+05	-.4117784+04	-.1978373+03	.3661458+05	-.1177518+05
6C+	-.2458573+05	-.3416096+05	-.1311269+05	-.3529933+05	-.1149744+06	-.7012388+05	-.1722226+05	.1194778+06	-.1320228+06
6C-	-.5345821+03	.2490723+03	-.1483301+03	.4348016+04	-.1210184+05	-.2605391+04	-.5948465+03	.2109646+05	-.5809002+05
7C+	-.3035081+05	-.4241415+05	-.1535707+05	-.4721406+05	-.1407594+06	-.8206521+05	-.2074763+05	.1507405+06	-.1830272+06
7C-	-.2128571+03	.1173405+03	.2614032+03	.6593797+04	-.1510315+05	-.7656476+04	-.8729060+03	.2434258+05	-.6293724+05
8C+	-.1721611+05	-.2386068+05	-.3255342+04	-.2417359+05	-.9087415+05	-.5045563+05	-.1195397+05	.1292103+06	-.1008481+06
8C-	.1377860+03	.9298090+03	.1903850+04	.6020168+04	-.1537361+05	-.5277935+04	-.4119232+03	.2839595+05	-.4411272+05
9C+	-.6691834+04	-.8621654+04	.1014200+04	-.1053047+05	-.3800656+05	-.1901654+05	-.3118723+04	.7967457+05	-.5050396+05
9C-	.3275570+03	.1082057+04	.2410235+04	.5214089+04	-.1066626+05	-.2747968+04	.2398256+02	.3009610+05	-.1986595+05
10C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
10C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
TC	-.8979290+05	-.1202593+06	-.1668052+05	-.1009307+06	-.5546385+06	-.2759761+06	-.6011055+05	.8493713+06	-.7032601+06
TC+	-.8953253+05	-.1228783+06	-.2494962+05	-.1291269+06	-.4761769+06	-.2525341+06	-.5828490+05	.6825135+06	-.4993061+06
TC-	-.2603714+03	.2618993+04	.8269078+04	.2819623+05	-.7846159+05	-.2344195+05	-.1825656+04	.1668578+06	-.2039540+06

Table 5.1 (Continued)

INSIDE SURFACE FLUXES, INTERNAL & AIR INFILTRATION LOADS

	.0000	.0000	.0000	.0000	.0000	.0000	.0000
	.0000	.0000	.0000	.0000	.0000	.0000	.0000
	.0000	.0000	.0000	.0000	.0000	.0000	.0000
	.0000	.0000	.0000	.0000	.0000	.0000	.0000

	EQUIP	OCPS	OCPL	INFILS	INFILL	TOTAL SENSBL	TOTAL LATENT
1 H	-.1643258+07	-.5721054+06	-.1153617+06	.4007302+07	.3984132+06	.6359687+07	.2830515+06
2 H	-.1300467+07	-.4689154+06	-.9388414+05	.2391878+07	.1391337+06	.3459563+07	.4524960+05
3 H	-.1159233+07	-.4517117+06	-.8826396+05	.1972998+07	.1492905+06	.2631418+07	.6102663+05
4 H	-.5421993+06	-.2089421+06	-.4038177+05	.7816179+06	.5046647+05	.9516251+06	.1008470+05
5 H	-.1305616+06	-.5304087+05	-.9575123+04	.1405865+06	.9627873+04	.1258949+06	.5275113+02
6 H	-.1037743+05	-.2981495+04	-.7265046+03	.8105137+04	.7272717+03	.2676792+04	.7670965+00
7 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
8 H	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
9 H	-.5386983+05	-.2236800+05	-.3792000+04	.5785551+05	.3794544+04	.5463092+05	.2543861+01
10 H	-.4952056+06	-.2083652+06	-.3815071+05	.6410702+06	.3817665+05	.6486103+06	.2595796+02
11 H	-.8208706+06	-.3240119+06	-.6349190+05	.1204188+07	.8068402+05	.1418555+07	.1719216+05
12 H	-.1442586+07	-.5266800+06	-.1049634+06	.2723068+07	.2023945+06	.3920112+07	.9743117+05
********	********	********	********	********	********	********	********
TH	-.7598628+07	-.2839122+07	-.5585913+06	.1392867+08	.1072709+07	.1957277+08	.5141178+06
1C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
1C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
2C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
3C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
4C+	-.1439341+06	-.2374020+05	-.1942389+05	-.3832910+05	.1387711+05	-.5017206+06	-.5546693+04
4C-	-.5201371+05	-.9213599+04	-.7538400+04	.5849474+04	.5865700+04	-.1185833+06	-.1672699+04
5C+	-.2931412+06	-.4932838+05	-.4035958+05	-.8528936+05	-.2923513+05	-.7596067+06	-.6959473+05
5C-	-.7749325+05	-.1321980+05	-.1081620+05	.5922787+04	.3613526+04	-.1281162+06	-.7202675+04
6C+	-.8059797+06	-.1454375+06	-.1189943+06	-.2773152+06	-.4763977+06	-.2315220+07	-.5953921+06
6C-	-.1242760+06	-.2453880+05	-.2007720+05	.8556999+04	-.3953214+05	-.2016336+06	-.5960934+05
7C+	-.1068030+07	-.1965478+06	-.1608118+06	-.3671331+06	-.1832526+06	-.3012553+07	-.3440645+06
7C-	-.1592893+06	-.2830740+05	-.2316060+05	.1364969+05	-.2346149+05	-.2681642+06	-.4662209+05
8C+	-.7240994+06	-.1309241+06	-.1071197+06	-.2132209+06	-.8127604+05	-.2041014+07	-.1883958+06
8C-	-.1446091+06	-.2467080+05	-.2018520+05	.1178346+05	-.1432498+05	-.2509670+06	-.3451019+05
9C+	-.3823618+06	-.6514198+05	-.5329798+05	-.1032887+06	-.2764925+06	-.1046264+07	-.3297904+06
9C-	-.1273555+06	-.2113980+05	-.1729620+05	.9653769+04	-.5272821+05	-.2275585+06	-.7002441+05
10C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
10C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
11C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C+	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
12C-	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000
********	********	********	********	********	********	********	********
TC	-.4102583+07	-.7322101+06	-.5990810+06	-.1029160+07	-.1153344+07	-.1088140+08	-.1752426+07
TC+	-.3417547+07	-.6111199+06	-.5000072+06	-.1084576+07	-.1032777+07	-.9676378+07	-.1532784+07
TC-	-.6850369+06	-.1210902+06	-.9907379+05	.5541618+05	-.1205676+06	-.1205023+07	-.2196414+06

Table 5.1 (Continued)

MONTH	MONTHLY HEATING HOURS	MONTHLY COOLING HOURS(+)	MONTHLY COOLING HOURS(-)	MONTHLY LOAD HOURS
1	713	0	0	713
2	569	0	0	569
3	529	0	0	529
4	246	55	20	321
5	63	114	30	207
6	4	312	42	358
7	0	413	57	470
8	0	282	53	335
9	26	147	48	221
10	234	0	0	234
11	373	0	0	373
12	634	0	0	634
**************************************				
TOTALS	3391	1323	250	4964

MAX COOLING LOAD = -16279. MONTH = 6 DAY = 18 HOUR = 12
MAX HEATING LOAD = 25127. MONTH = 12 DAY = 12 HOUR = 7
TOTAL COOLING CONSUMPTION PER DAY = 0. BTU
TOTAL HEATING CONSUMPTION PER DAY = 115181. BTU
TOTAL COOLING CONSUMPTION FOR 1 ROOMS = -.12634+08 BTU
TOTAL HEATING CONSUMPTION FOR 1 ROOMS = .20087+08 BTU

Load components are calculated only during actual heating or cooling hours. This is an important point because the number of heating or cooling hours may change as the envelope design, occupancy schedule, or thermostat settings change. This is particularly true of heating hours, which may change significantly as the overall thermal integrity of the building shell is improved. For example, in Washington, D.C., the uninsulated prototype house with night setback to 60°F has 4301 computed heating hours in the TRY year while the superinsulated house with night setback has 2803 computed heating hours.[1] Cooling hours (i.e., the number of hours in which any cooling is required) above the indoor thermostat setpoint change relatively little as the design is changed, since internal and solar loads must still be removed. For the same prototype house, the uninsulated case had 1322 cooling hours while the superinsulated case had 1323 hours. (The one-hour increase in cooling hours was due to insulating the floor, which reduced the heat-sink effect of the crawlspace.)

NBSLD has been validated in several studies for its accuracy in calculating heating and cooling loads in different buildings for a variety of climatic conditions. Two studies on unoccupied structures[2,3] that correlated calculated and measured loads showed that NBSLD can closely simulate heating and cooling loads under controlled conditions. A more recent, and more relevant, study was conducted by Cornell University on three occupied dwelling units in Twin Rivers, N.J.[4] This study indicates that NBSLD accurately simulates the true thermal performance of occupied buildings when the thermal enclosure and usage schedule are defined accurately. In the study, actual weather data and usage schedules were used in the NBSLD program. The correlations between predicted and measured heating requirements, both in terms of hourly load data and cumulative energy usage, were excellent. Two of the three cases were within one percent of the measured data; the third deviated by less than ten percent.

NBSLD and its expanded output version appear to be the best available means for calculating component performance in buildings. However, the programs still have certain shortcomings, primarily related to their ability to model specific envelope components. Particular deficiencies involve the thermal modeling of

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1 See table 6.9.

2 B. Peavy, F. Powell, and D. Burch, Dynamic Thermal Peformance of an Experimental Masonry Building, BSS 45, National Bureau of Standards, Washington, D.C., 1972.

3 B. Peavy, D. Burch, F. Powell, and C.M. Hunt, Comparison of Measured and Computer Predicted Thermal Peformance of a Four-Bedroom Wood-Frame Townhouse, BSS 57, National Bureau of Standards, Washington, D.C., 1973.

4 Roberts, Nall, Rogers, Greenburg, "Comparison of Computer-Predicted Thermal Loads with Measured Data from Three Occupied Townhouses," ASHRAE Transactions, Vol. 83, Part I, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1978.

attics, basements, slab floors, interior partitions and furnishings. As these algorithms are improved in the future, NBSLD-XO will provide better estimates of the thermal performance of these components.

Section 4.1 discussed the shortcomings of modeling only the exterior envelope surfaces without internal partitions. Despite these shortcomings, internal partitions were not included in the NBSLD analysis of the prototype house. In order to model partition walls with NBSLD, the heating and cooling loads in each partitioned area must be calculated separately with no exchange of surplus heat or cooling between or among zones. This can seriously distort the total heating and cooling loads for all partitioned areas. South-facing zones frequently will not require heating during mid-afternoon hours and often have excess heat available. At the same time, north-facing zones will require heating that could be offset or eliminated if the excess heat in the south-facing zones were made available. The annual total heating requirements for all zones will therefore be significantly greater than for the house modeled as one zone (i.e., with no partitions). Moreover, as the overall building is better insulated, this distortion becomes larger since there will be more excess heat available in the south-facing zones. On the other hand, the distortions due to the lack of partition walls diminish as the overall envelope becomes better insulated. This is because the inside surface temperatures of the walls approach room air temperature, much as would the internal partitions, so that radiation exchange would be minimized. In order to reduce the distortion further, 90 percent of the direct solar gain through windows is assumed to fall on the floor, rather than the other inside envelope surfaces. (The remaining 10 percent is spread evenly over the other inside surfaces.) This is a reasonable assumption since the floor generally is darker than the walls and ceiling and therefore absorbs the majority of sunlight reflected by other surfaces. (However, this may exaggerate the heating energy savings and especially the cooling energy increases due to insulating the floor.) In general, modeling the house with no partition walls will produce smaller errors in calculating the effects of envelope modifications than modeling the house with thermally uncoupled zones.

Prior to calculating the annual heating and cooling requirements of the house at its different stages of modification, the hourly crawlspace temperatures for the year were calculated using a separate NBSLD analysis. Indoor thermostat set points were used as indoor temperatures for this analysis. (During those hours when the indoor temperature floated between the set points, there was no heating or cooling load, so that the resulting crawlspace temperature in those hours would be of little or no consequence in estimating the heating and cooling requirements of the house.) The crawlspace was modeled as an enclosed, vented area with two air changes per hour under winter design conditions.

6. THERMAL ANALYSIS AND PRIORITY RANKING OF ENVELOPE MODIFICATIONS

The expanded output version of the National Bureau of Standards Load Determination program (NBSLD-XO) was used to determine the successive reductions in heating and cooling loads for the prototype ranch house as 15 component modifications were made sequentially to the envelope design. The analysis was carried out for 14 cities. Most of these cities were selected because they represent a broad range of climates in the continental United States. Several cities were added to the initial selection to provide data for a parallel research project and were included to enlarge the data sample.

Test Reference Year[1] (TRY) weather tapes, which have been selected as the most typical of average climate data available, were used to simulate hour-by-hour weather data in these cities. Table 6.1 lists the cities, reference year used, and number of heating and cooling degree days (base 65°F) in the TRY weather data for that year.

6.1 PRIORITY RANKING OF ENVELOPE MODIFICATIONS

To determine the sequence in which the envelope modifications are to be analyzed in this report, a preliminary ranking of modifications, in order of decreasing cost effectiveness, was made as shown in table 6.2. (The need for such a ranking procedure is discussed in section 3.2.4.) This ordering was established for reductions in heating requirements only; these reductions were initially computed for the 1200 ft^2 single-story house, based on TRY climate data for Washington, D.C. Modification cost data are based on table 4.6. Since the savings in heating requirements only were considered at this point, the cost per unit of heating energy is not important in establishing the priority ordering of the modifications. However, energy costs are important in determining the extent to which these modifications are actually cost-effective on a life-cycle basis.

The priority ordering shown in table 6.2 is quite similar for all the climate regions examined in this report when only heating requirements are considered. The only significant exception is for floor insulation. Relative to the other modifications examined, floor insulation tends to have less than proportional effects in reducing heating requirements in the milder climates and more than proportional effects in the colder climates.[2] A similar priority order was found when cooling requirements were examined with the following exceptions:

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[1] Stamper, E., "Weather Data," ASHRAE Journal, Feb. 1977, p. 47.

[2] While this result is inherently logical, it may be somewhat exaggerated because of the modeling procedure which places 90 percent of the direct solar gain through windows on the floor. In colder climates, the sun will be shining more during heating hours than in milder climates, where the majority of heating is during non-daylight hours. Thus the inside floor surface will tend to be warmer in the colder climates over a greater percentage of the heating hours.

Table 6.1 14 Selected Cities, TRY Reference Year, and Degree Days Used in Thermal Analysis

LOCATION	TRY YEAR	DEGREE DAYS (BASE 65°F) HEATING	COOLING
Miami	1964	130	4176
Phoenix	1951	1571	3434
San Antonio	1960	1897	2739
Fort Worth	1975	2373	2495
San Francisco	1974	3557	35
Sacramento	1962	3144	778
Atlanta	1975	2959	1359
Washington, D.C.	1957	4161	1482
Seattle	1960	5562	143
Kansas City	1968	5058	1485
Boston	1969	5781	667
Chicago (Midway)	1974	6103	731
Madison	1974	7311	454
Minneapolis	1970	8316	919

Table 6.2 Ranking of Modifications[a]

Rank	Component	Modification TO	FROM	ΔU	ΔCost[b]
1	Attic insulation	R-11	R-0	0.488	$235
2	Wall insulation	R-11	R-0	0.136	220
3	Attic insulation	R-19	R-11	0.035	110
4	Floor insulation	R-11	R-0	0.165	280
5	Window glazing	Double	Single	0.57	225
6	Attic insulation	R-30	R-19	0.018	170
7	Floor insulation	R-19	R-11	0.021	125
8	Sliding glass door (glazing)	Double	Single	0.467	180
9	Wall insulation	R-13	R-11	0.007	70
10	Attic insulation	R-38	R-30	0.007	110
11	Wall insulation	R-19	R-13	0.018	290
12	Window glazing	Triple	Double	0.200	255
13	Attic insulation	R-49	R-38	0.006	170
14	Wall insulation	R-23	R-18	0.011	290
15	Door	Storm	No Storm	0.160	150

[a] Modifications are ranked in decreasing order of cost effectiveness in terms of reducing annual heating requirements as determined in the NBSLD analysis.

[b] From table 4.7. These costs are in end-year 1979 dollars.

(1) Floor insulation actually increased the cooling requirements because it eliminated the heat-sink effect of the crawlspace during much or all of the cooling season. Again, this effect may be somewhat exaggerated because the NBSLD program used assumes that 90 percent of the direct solar gain falls on the floor. However, it is clear that a ranking based only on reductions in cooling requirements would eliminate floor insulation entirely.

(2) The effectiveness of attic insulation relative to the wall and window modifications increases slightly during cooling periods, while the relative effectiveness of multiple glazing decreases slightly in the milder summer climates.

Ideally, the reductions in both heating and cooling requirements resulting from each modification should be considered in the priority ranking process. More precisely, the reduction in total life-cycle heating and cooling expenditures due to each modification should be the basis for the savings used in their ranking. This means that both the relative costs of each type of energy used and the relative efficiency of the heating and cooling equipment installed should be evaluated. Thus, the proper ranking should be calculated separately for each location considered; the resulting thermal analyses would be appropriate only for those energy costs and equipment efficiencies assumed. Because a more generalized approach is needed to accomplish the goal of this report, the ranking of all 15 modifications in the 14 locations is based only on reductions in annual heating requirements. It is important to point out that the priority ranking of the modifications may change as the costs of the modifications change relative to one another. Changes in the ranking will significantly affect the subsequent savings if there is a substantial amount of interdependence among the components being modified. The extent to which this may affect the general conclusions of this report will be discussed at a later point in this section.

6.2 RESULTS OF THERMAL ANALYSIS

6.2.1 Heating and Cooling Requirements

Table 6.3 provides the tabulation of the annual heating requirements calculated for the prototype house, modified cumulatively as indicated in each of the 14 locations. H0 designates the basic house with its uninsulated envelope. H1 through H15 represent 15 variations of the prototype house; each sequential variation includes all previous envelope modifications plus one additional new one. The 14 locations are listed in order of increasing heating requirements. Annual heating requirements in seven of these locations are plotted against corresponding cumulative conservation costs in figure 6.1 to demonstrate visually the relationship between energy consumption and energy conservation investment in those climates.

In order to reduce the number of computer runs needed to calculate the effect of all 15 modifications in each of the 14 cities, the effects of some of the modifications were determined by interpolation in most cases. The effects of all 15 modifications were calculated individually in three locations: San Antonio, Texas (mild winter, warm summer), Washington, D.C. (moderate winter

Table 6.3 Annual Heating Requirements by City and Cumulative Modification Level (Million Btu)

House Designator	Modifications (Cumulative)	Miami	Phoenix	San Antonio	Fort Worth	San Francisco
H0	Base House	0.978	14.164	20.349	24.886	26.930
H1	R-11 Attic	0.542	8.432	13.908	16.945	16.981
H2	R-11 Walls	0.335	5.499	10.578	12.746	11.555
H3	R-19 Attic	0.278	4.683	9.650	11.573	10.036
H4	R-11 Floor	0.258	4.438	8.450	10.179	7.937
H5	DBL Window	0.197	3.527	7.000	8.450	6.082
H6	R-30 Attic	0.174	3.174	6.429	7.763	5.342
H7	R-19 Floor	0.169	3.057	6.194	7.450	4.990
H8	Double SGD	0.145	2.694	5.613	6.756	4.243
H9	R-13 Walls	0.138	2.578	5.424	6.527	3.997
H10	R-38 Attic	0.129	2.445	5.207	6.265	3.714
H11	R-19 Walls	0.108	2.091	4.651	5.619	3.111
H12	TPL Window	0.092	1.815	4.214	5.110	2.635
H13	R-49 Attic	0.086	1.705	4.036	4.901	2.441
H14	R-23 Walls	0.075	1.527	3.749	4.563	2.127
H15	Storm Door	0.072	1.468	3.655	4.453	2.025

House Designator	Modifications (Cumulative)	Sacramento	Atlanta	Washington	Seattle	Kansas City
H0	Base House	31.492	32.476	50.155	66.477	68.301
H1	R-11 Attic	21.025	23.044	37.242	49.342	52.246
H2	R-11 Walls	15.271	17.942	29.863	39.249	42.864
H3	R-19 Attic	13.659	16.514	27.789	36.452	40.254
H4	R-11 Floor	11.668	14.125	23.242	30.061	34.905
H5	DBL Window	9.604	11.952	20.087	25.618	30.813
H6	R-30 Attic	8.773	11.073	18.759	23.776	29.109
H7	R-19 Floor	8.350	10.610	17.826	22.468	27.903
H8	Double SGD	7.518	9.733	16.537	20.632	26.218
H9	R-13 Walls	7.241	9.439	16.088	19.997	25.634
H10	R-38 Attic	6.922	9.102	15.570	19.272	24.965
H11	R-19 Walls	6.126	8.259	14.318	17.584	23.339
H12	TPL Window	5.493	7.588	13.299	16.183	21.993
H13	R-49 Attic	5.230	7.307	12.858	15.585	21.417
H14	R-23 Walls	4.805	6.854	12.144	14.604	20.475
H15	Storm Door	4.667	6.708	11.918	14.294	20.177

House Designator	Modifications (Cumulative)	Boston	Chicago	Madison	Minneapolis
H0	Base House	81.027	81.287	102.040	125.890
H1	R-11 Attic	63.054	62.638	79.745	100.560
H2	R-11 Walls	52.405	51.533	66.110	84.714
H3	R-19 Attic	49.461	48.470	62.395	80.440
H4	R-11 Floor	41.698	41.614	54.121	71.115
H5	DBL Window	36.672	36.653	48.104	63.974
H6	R-30 Attic	34.603	34.609	45.657	61.109
H7	R-19 Floor	33.127	33.151	43.895	59.026
H8	Double SGD	31.040	31.093	41.377	56.010
H9	R-13 Walls	30.321	30.383	40.513	54.982
H10	R-38 Attic	29.503	29.575	39.538	53.830
H11	R-19 Walls	27.624	27.629	37.160	51.065
H12	TPL Window	26.050	25.994	35.120	48.648
H13	R-49 Attic	25.383	24.302	34.269	47.653
H14	R-23 Walls	24.283	24.159	32.846	45.969
H15	Storm Door	23.935	23.798	32.396	45.437

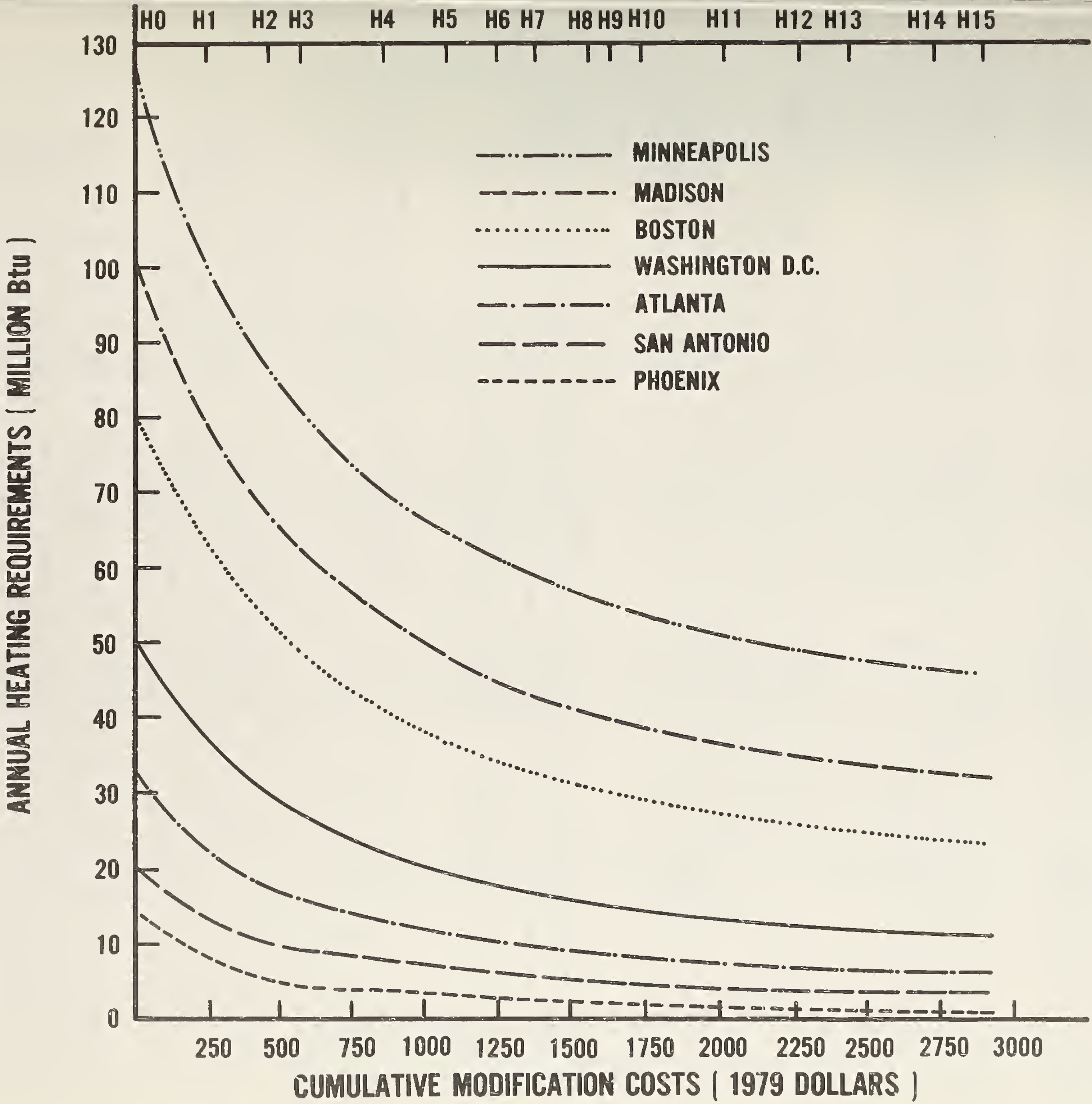

Figure 6.1 Annual heating requirements as reduced by energy conserving modifications in selected cities (1200 sq. ft. house)

and summer), and Minneapolis, Minn. (severe winter, mild summer). In the other 11 locations, NBSLD calculations were only made for the H0, H3, H4, H10 and H15 house variations. Estimates of the heating and cooling requirements for the other ten variations in those locations were then interpolated between those five points, using the complete data sets from the three cities as a guide. This procedure appears to provide excellent results for estimating the effects of all 15 modifications in all locations.

Table 6.4 provides the incremental reduction in annual heating requirements due to each modification in each location examined, based on the differences between the heating requirements shown in table 6.3. Except in the mildest climates, the greatest reductions occur for the R-11 insulation in the attic, walls, and floor and the double glazing. In the mildest climates, the floor insulation is relatively less effective than in the remaining climates.

Table 6.5 provides the energy savings-to-cost ratio for each modification in each location, where energy savings are expressed in terms of a 1,000 Btu reduction in annual heating requirements. This table demonstrates the relative stability of the ranking of modifications in terms of decreasing savings-to-cost ratios for each location. However, in the milder heating climates the floor insulation modifications are ranked too high. (In fact it will be seen that floor insulation should not be used in those climates if air conditioning is used.)

Table 6.6 provides the tabulation of the annual cooling requirements for the prototype house, modified cumulatively using the priority ordering established in the analysis of the heating requirements. In all cases, the use of insulation in the floor increases rather than reduces annual cooling requirements. Annual cooling requirements in seven of these locations are plotted against corresponding cumulative conservation costs in figure 6.2.

Table 6.7 provides the reduction or increase in annual cooling requirements due to each modification in each location based on table 6.6. Table 6.8 provides the energy savings-to-cost ratio for each modification in each location, where energy savings are now expressed in terms of a 1,000 Btu reduction in annual cooling requirements. R-11 insulation in the attic and walls is the most effective means of reducing cooling requirements here. Storm doors, which show the least savings here, would be better utilized in the non-heating season if the glass inserts were removed and replaced with screens. However, no estimate of the savings due to this action can be reasonably calculated. The data in table 6.8 indicate the somewhat different priority ranking that would be given to the same modifications if only cooling savings were considered.

A second series of NBSLD analyses were made for Washington, D.C. in which the priority order was established based on reductions in annual cooling requirements rather than annual heating requirements. The calculated savings due to the subsequent modifications were similar to those using the priority ordering

Table 6.4 Reduction in AHR by City and Incremental Modification (Million Btu)

Modifications	Miami	Phoenix	San Antonio	Fort Worth	San Francisco
R-11 Attic	0.436	5.732	6.441	7.941	9.949
R-11 Walls	0.207	2.932	3.330	4.199	5.426
R-19 Attic	0.057	0.816	0.928	1.173	1.519
R-11 Floor	0.020	0.245	1.200	1.394	2.099
DBL Window	0.061	0.911	1.450	1.729	1.855
R-30 Attic	0.023	0.353	0.571	0.687	0.741
R-19 Floor	0.005	0.117	0.235	0.313	0.352
Double SGD	0.024	0.363	0.581	0.695	0.746
R-13 Walls	0.007	0.116	0.189	0.228	0.246
R-38 Attic	0.009	0.133	0.217	0.262	0.283
R-19 Walls	0.021	0.354	0.556	0.646	0.603
TPL Window	0.016	0.276	0.437	0.510	0.475
R-49 Attic	0.006	0.110	0.178	0.209	0.194
R-23 Walls	0.010	0.178	0.287	0.337	0.314
Storm Door	0.003	0.059	0.094	0.110	0.102

Modifications	Sacramento	Atlanta	Washington	Seattle	Kansas City
R-11 Attic	10.467	9.432	12.913	17.135	16.055
R-11 Walls	5.754	5.103	7.379	10.092	9.383
R-19 Attic	1.612	1.428	2.074	2.797	2.610
R-11 Floor	1.991	2.389	4.547	6.391	5.349
DBL Window	2.064	2.173	3.155	4.444	4.092
R-30 Attic	0.831	0.878	1.328	1.842	1.703
R-19 Floor	0.423	0.463	0.933	1.308	1.206
Double SGD	0.832	0.877	1.289	1.835	1.685
R-13 Walls	0.277	0.293	0.449	0.635	0.584
R-38 Attic	0.319	0.337	0.518	0.725	0.669
R-19 Walls	0.796	0.843	1.252	1.688	1.626
TPL Window	0.633	0.672	1.019	1.401	1.346
R-49 Attic	0.263	0.280	0.441	0.598	0.576
R-23 Walls	0.425	0.453	0.714	0.980	0.942
Storm Door	0.138	0.146	0.226	0.310	0.298

Modifications	Boston	Chicago	Madison	Minneapolis
R-11 Attic	17.973	18.649	22.295	25.330
R-11 Walls	10.650	11.105	13.635	15.846
R-19 Attic	2.944	3.063	3.715	4.274
R-11 Floor	7.763	6.856	8.274	9.325
DBL Window	5.026	4.961	6.017	7.141
R-30 Attic	2.069	2.044	2.447	2.865
R-19 Floor	1.477	1.458	1.762	2.083
Double SGD	2.086	2.058	2.518	3.016
R-13 Walls	0.719	0.710	0.863	1.028
R-38 Attic	0.818	0.808	0.976	1.152
R-19 Walls	1.879	1.946	2.378	2.765
TPL Window	1.574	1.635	2.040	2.417
R-49 Attic	0.667	0.692	0.851	0.995
R-23 Walls	1.100	1.143	1.423	1.684
Storm Door	0.348	0.361	0.450	0.532

Table 6.5 Reduction in AHR (1000 Btu) per Dollar of Initial Cost by City and Incremental Modification

Modification	Miami	Phoenix	San Antonio	Fort Worth	San Francisco
R-11 Attic	1.86	24.39	27.41	33.79	42.34
R-11 Walls	0.94	13.33	15.14	19.09	24.66
R-19 Attic	0.52	7.42	8.44	10.66	13.81
R-11 Floor	0.07	0.88	4.29	4.98	7.50
DBL Window	0.27	4.05	6.44	7.68	8.24
R-30 Attic	0.14	2.07	3.36	4.04	4.36
R-19 Floor	0.04	0.98	1.88	2.50	2.82
Double SGD	0.13	2.02	3.23	3.86	4.15
R-13 Walls	0.11	1.66	2.70	3.26	3.52
R-38 Attic	0.08	1.21	1.97	2.38	2.57
R-19 Walls	0.07	1.22	1.92	2.23	2.08
TPL Window	0.06	1.08	1.71	2.00	1.86
R-49 Attic	0.04	0.65	1.05	1.23	1.14
R-23 Walls	0.03	0.61	0.99	1.16	1.08
Storm Door	0.02	0.39	0.63	0.73	0.68

Modification	Sacramento	Atlanta	Washington	Seattle	Kansas City
R-11 Attic	44.54	40.14	54.95	72.92	68.32
R-11 Walls	26.15	23.19	33.54	45.87	42.65
R-19 Attic	14.66	12.98	18.85	25.43	23.73
R-11 Floor	7.11	8.53	16.24	22.82	19.10
DBL Window	9.17	9.66	14.02	19.75	18.19
R-30 Attic	4.89	5.17	7.81	10.83	10.02
R-19 Floor	3.38	3.71	7.46	10.47	9.65
Double SGD	4.62	4.87	7.16	10.20	9.36
R-13 Walls	3.96	4.19	6.41	9.07	8.34
R-38 Attic	2.90	3.07	4.71	6.59	6.08
R-19 Walls	2.75	2.91	4.32	5.82	5.61
TPL Window	2.48	2.63	4.00	5.50	5.28
R-49 Attic	1.55	1.65	2.59	3.52	3.39
R-23 Walls	1.47	1.56	2.46	3.38	3.25
Storm Door	0.92	0.98	1.51	2.07	1.99

Modification	Boston	Chicago	Madison	Minneapolis
R-11 Attic	76.48	79.36	94.87	107.79
R-11 Walls	48.41	50.48	61.98	72.03
R-19 Attic	26.76	27.84	33.77	38.85
R-11 Floor	27.72	24.49	29.55	33.30
DBL Window	22.34	22.05	26.74	31.74
R-30 Attic	12.17	12.02	14.40	16.85
R-19 Floor	11.81	11.66	14.10	16.66
Double SGD	11.59	11.43	13.99	16.76
R-13 Walls	10.27	10.14	12.33	14.69
R-38 Attic	7.44	7.35	8.87	10.47
R-19 Walls	6.48	6.71	8.20	9.53
TPL Window	6.17	6.41	8.00	9.48
R-49 Attic	3.93	4.07	5.00	5.85
R-23 Walls	3.79	3.94	4.91	5.81
Storm Door	2.32	2.41	3.00	3.55

Table 6.6 Annual Cooling Requirements by City and Cumulative Modification Level (Million Btu)

House Designator	Modifications (Cumulative)	City				
		Miami	Phoenix	San Antonio	Fort Worth	San Francisco
H0	Base House	45.512	51.511	32.307	32.168	1.111
H1	R-11 Attic	41.657	44.639	28.481	28.130	0.894
H2	R-11 Walls	38.922	37.564	25.774	25.209	0.731
H3	R-19 Attic	37.959	35.511	24.820	24.192	0.680
H4	R-11 Floor	39.508	36.688	25.769	25.091	0.842
H5	DBL Window	38.881	34.965	25.150	24.451	0.810
H6	R-30 Attic	38.228	34.060	24.501	23.790	0.781
H7	R-19 Floor	38.327	34.144	24.558	23.845	0.808
H8	Double SGD	37.961	33.194	24.196	23.471	0.785
H9	R-13 Walls	37.784	32.908	24.020	23.292	0.776
H10	R-38 Attic	37.515	32.533	23.753	23.020	0.764
H11	R-19 Walls	36.933	31.553	23.203	22.447	0.732
H12	TPL Window	36.459	30.388	22.768	21.984	0.706
H13	R-49 Attic	36.209	29.980	22.531	21.738	0.696
H14	R-23 Walls	35.978	29.565	22.314	21.511	0.690
H15	Storm Door	35.915	29.407	22.256	21.449	0.687
		Sacramento	Atlanta	Washington	Seattle	Kansas City
H0	Base House	16.205	14.772	14.794	1.806	17.532
H1	R-11 Attic	12.784	12.046	12.393	1.452	15.050
H2	R-11 Walls	10.461	10.413	10.914	1.191	13.510
H3	R-19 Attic	9.623	9.771	10.349	1.108	12.924
H4	R-11 Floor	10.983	10.601	11.466	1.350	14.158
H5	DBL Window	10.582	10.358	11.209	1.301	13.860
H6	R-30 Attic	10.077	10.015	10.834	1.256	13.443
H7	R-19 Floor	10.286	10.130	11.004	1.296	13.623
H8	Double SGD	10.046	9.978	10.847	1.260	13.441
H9	R-13 Walls	9.913	9.889	10.750	1.247	13.333
H10	R-38 Attic	9.705	9.748	10.596	1.228	13.162
H11	R-19 Walls	9.277	9.456	10.284	1.173	12.817
H12	TPL Window	8.970	9.261	10.080	1.129	12.585
H13	R-49 Attic	8.784	9.137	9.944	1.112	12.435
H14	R-23 Walls	8.618	9.028	9.824	1.100	12.302
H15	Storm Door	8.577	9.003	9.797	1.095	12.271
		Boston	Chicago	Madison	Minneapolis	
H0	Base House	5.124	6.658	5.928	9.490	
H1	R-11 Attic	4.385	5.499	4.956	7.936	
H2	R-11 Walls	3.857	4.702	4.277	6.905	
H3	R-19 Attic	3.684	4.430	4.049	6.540	
H4	R-11 Floor	4.279	5.088	4.651	7.513	
H5	DBL Window	4.174	4.948	4.531	7.321	
H6	R-30 Attic	4.064	4.791	4.404	7.082	
H7	R-19 Floor	4.158	4.895	4.499	7.236	
H8	Double SGD	4.084	4.798	4.415	7.109	
H9	R-13 Walls	4.052	4.754	4.378	7.044	
H10	R-38 Attic	4.007	4.690	4.326	6.946	
H11	R-19 Walls	3.894	4.533	4.192	6.724	
H12	TPL Window	3.805	4.414	4.090	6.565	
H13	R-49 Attic	3.767	4.358	4.043	6.479	
H14	R-23 Walls	3.738	4.313	4.012	6.407	
H15	Storm Door	3.728	4.300	4.000	6.388	

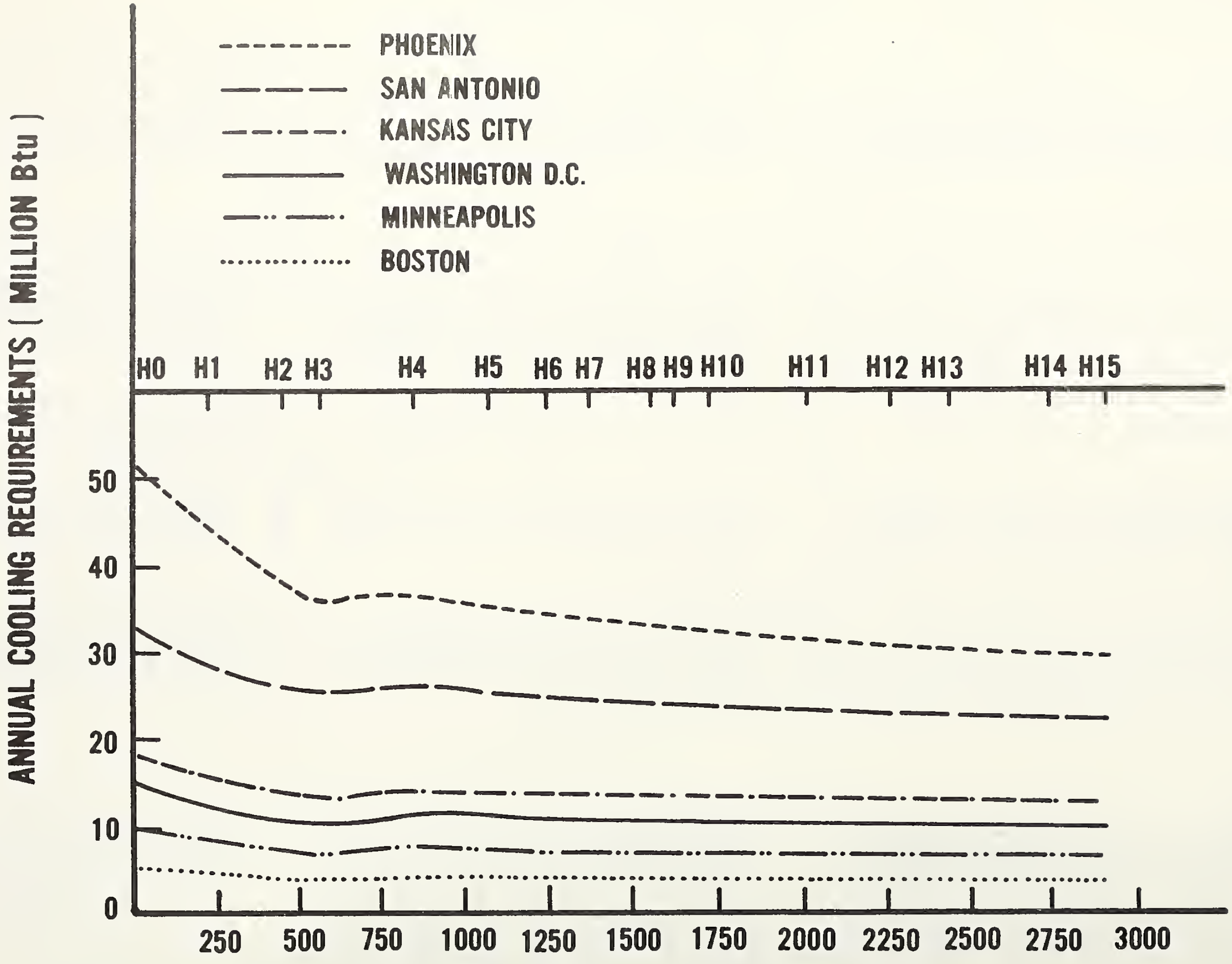

Figure 6.2 Annual cooling requirements ($t_o \geq t_i$) as reduced by energy conserving modifications in selected cities (1200 ft^2 house)

Table 6.7 Reduction in ACR by City and Incremental Modification (Million Btu)

Modification	Miami	Phoenix	San Antonio	Fort Worth	San Francisco
R-11 Attic	3.855	6.872	3.826	4.039	0.217
R-11 Walls	2.736	7.076	2.707	2.921	0.163
R-19 Attic	0.963	2.053	0.954	1.017	0.051
R-11 Floor	-1.549	-1.177	-0.949	-0.899	-0.162
DBL Window	0.627	1.723	0.619	0.641	0.032
R-30 Attic	0.653	0.905	0.649	0.661	0.029
R-19 Floor	-0.099	-0.084	-0.057	-0.055	-0.027
Double SGD	0.366	0.951	0.362	0.374	0.024
R-13 Walls	0.177	0.286	0.176	0.180	0.009
R-38 Attic	0.269	0.375	0.267	0.272	0.012
R-19 Walls	0.582	0.980	0.550	0.573	0.032
TPL Window	0.473	1.166	0.435	0.462	0.026
R-49 Attic	0.251	0.408	0.237	0.247	0.009
R-23 Walls	0.231	0.415	0.217	0.227	0.007
Storm Door	0.063	0.157	0.058	0.062	0.003

Modification	Sacramento	Atlanta	Washington	Seattle	Kansas City
R-11 Attic	3.421	2.726	2.401	0.354	2.482
R-11 Walls	2.323	1.633	1.479	0.262	1.540
R-19 Attic	0.838	0.642	0.565	0.083	0.586
R-11 Floor	-1.360	-0.830	-1.117	-0.242	-1.234
DBL Window	0.401	0.243	0.257	0.049	0.299
R-30 Attic	0.506	0.342	0.375	0.046	0.417
R-19 Floor	-0.209	-0.115	-0.170	-0.041	-0.180
Double SGD	0.240	0.152	0.157	0.036	0.181
R-13 Walls	0.133	0.090	0.097	0.014	0.108
R-38 Attic	0.208	0.141	0.154	0.019	0.171
R-19 Walls	0.428	0.292	0.312	0.055	0.345
TPL Window	0.307	0.195	0.204	0.045	0.232
R-49 Attic	0.186	0.124	0.136	0.017	0.150
R-23 Walls	0.167	0.108	0.120	0.012	0.133
Storm Door	0.041	0.025	0.027	0.005	0.031

Modification	Boston	Chicago	Madison	Minneapolis
R-11 Attic	0.739	1.159	0.972	1.554
R-11 Walls	0.528	0.797	0.679	1.031
R-19 Attic	0.173	0.272	0.228	0.365
R-11 Floor	-0.595	-0.658	-0.602	-0.973
DBL Window	0.105	0.140	0.120	0.192
R-30 Attic	0.110	0.156	0.128	0.239
R-19 Floor	-0.094	-0.104	-0.095	-0.154
Double SGD	0.075	0.097	0.084	0.127
R-13 Walls	0.032	0.044	0.037	0.065
R-38 Attic	0.045	0.064	0.052	0.098
R-19 Walls	0.113	0.157	0.134	0.222
TPL Window	0.089	0.119	0.102	0.159
R-49 Attic	0.038	0.056	0.047	0.086
R-23 Walls	0.029	0.045	0.031	0.019
Storm Door	0.010	0.013	0.012	0.072

Table 6.8 Reduction in ACR (1000 Btu) per Dollar of Initial Cost by City and Incremental Modification

Modification	Miami	Phoenix	San Antonio	Fort Worth	San Francisco
R-11 Attic	16.40	29.24	16.28	17.19	0.92
R-11 Walls	12.43	32.16	12.30	13.28	0.74
R-19 Attic	8.75	18.66	8.67	9.24	0.46
R-11 Floor	-5.53	-4.20	-3.39	-3.21	-0.58
DBL Window	2.78	7.66	2.75	2.85	0.14
R-30 Attic	3.84	5.32	3.82	3.89	0.17
R-19 Floor	-0.79	-0.68	-0.46	-0.44	-0.22
Double SGD	2.03	5.28	2.01	2.08	0.13
R-13 Walls	2.53	4.08	2.51	2.57	0.13
R-38 Attic	2.44	3.41	2.43	2.47	0.11
R-19 Walls	2.01	3.38	1.90	1.98	0.11
TPL Window	1.86	4.57	1.71	1.81	0.10
R-49 Attic	1.47	2.40	1.39	1.45	0.06
R-23 Walls	0.80	1.43	0.75	0.78	0.02
Storm Door	0.42	1.05	0.39	0.41	0.02

Modification	Sacramento	Atlanta	Washington	Seattle	Kansas City
R-11 Attic	14.56	11.60	10.22	1.50	10.56
R-11 Walls	10.56	7.42	6.72	1.19	7.00
R-19 Attic	7.62	5.84	5.14	0.75	5.33
R-11 Floor	-4.86	-2.96	-3.99	-0.86	-4.41
DBL Window	1.78	1.08	1.14	0.22	1.33
R-30 Attic	2.97	2.01	2.21	0.27	2.45
R-19 Floor	-1.67	-0.92	-1.36	-0.32	-1.44
Double SGD	1.33	0.84	0.87	0.20	1.01
R-13 Walls	1.90	1.28	1.39	0.20	1.55
R-38 Attic	1.89	1.28	1.40	0.17	1.56
R-19 Walls	1.48	1.01	1.08	0.19	1.19
TPL Window	1.20	0.77	0.80	0.18	0.91
R-49 Attic	1.09	0.73	0.80	0.10	0.88
R-23 Walls	0.57	0.37	0.41	0.04	0.46
Storm Door	0.27	0.17	0.18	0.03	0.20

Modification	Boston	Chicago	Madison	Minneapolis
R-11 Attic	3.15	4.93	4.14	6.61
R-11 Walls	2.40	3.62	3.09	4.69
R-19 Attic	1.58	2.47	2.07	3.32
R-11 Floor	-2.12	-2.35	-2.15	-3.47
DBL Window	0.47	0.62	0.53	0.85
R-30 Attic	0.64	0.92	0.75	1.41
R-19 Floor	-0.75	-0.83	-0.76	-1.23
Double SGD	0.42	0.54	0.47	0.71
R-13 Walls	0.45	0.63	0.53	0.93
R-38 Attic	0.41	0.58	0.47	0.89
R-19 Walls	0.39	0.54	0.46	0.77
TPL Window	0.35	0.47	0.40	0.62
R-49 Attic	0.22	0.33	0.28	0.51
R-23 Walls	0.10	0.15	0.11	0.25
Storm Door	0.06	0.09	0.08	0.13

for heating savings, except that floor insulation is not used.[1] As a result, the ranking based on reductions in heating requirements alone can be used with considerable confidence.

Tables 6.9 and 6.10 show the number of annual hours during which heating and cooling loads, respectively, actually occurred in the NBSLD calculations. Heating hours are shown for five variations of the basic prototype house (H0, H3, H4, H10, and H15, the five variations actually modeled with NBSLD in all 14 locations examined). Cooling hours where the outdoor temperature is greater than or equal to the thermostat setpoint ($t_o \geq t_i$) vary insignificantly as the envelope is upgraded. Improvements in the thermal integrity of the envelope significantly reduce the number of hours during which space heating requirements occur. This is because the balance point, that is, the outdoor temperature below which heating is required, is reduced as the rate of heat loss from the envelope is reduced while solar and internal heat gains are held constant. Approximate balance points have been calculated and these are discussed in section 7.

Economic analyses to determine optimal combinations of design modifications will be discussed in section 8. The remainder of this section outlines some of the other factors that might influence the envelope design and operation, based on the NBSLD analyses made for this report.

6.2.2 Maximum Hourly Heating and Cooling Loads

Tables 6.11 and 6.12 provide the calculated maximum hourly heating (with night setback) and cooling loads respectively for the base case (H0) and four modified variations (H3, H4, H10, H15) of the prototype house for the 14 locations examined. These are the maximum hourly loads corresponding to the annual heating and cooling requirements shown in tables 6.3 and 6.6. Figures 6.3 and 6.4 demonstrate, in graphic form, the relationship between maximum heating and cooling loads, respectively, and the overall level of energy conservation investment in the building envelope. Note that the range of maximum loads is significantly less than the range of annual heating and cooling requirements, particularly for the latter.

Although the modifications considered significantly affect maximum heating and cooling requirements, the incremental effects are relatively small as the less cost-effective measures are implemented. Moreover, in the majority of cases, space heating and cooling equipment capacities do not vary enough to take advantage of small reductions in design loads. If a decrease in the maximum load allows the use of smaller equipment at a cost savings to the building user, this should be considered in a benefit-cost analysis in incremental envelope modifications.

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[1] The removal of floor insulation from the ordering of modifications tended to result in somewhat smaller heating savings due to the subsequent modification of the other envelope components in the NBSLD simulations. However, the validity of this result is questionable due to the nature of the radiation exchange algorithm in NBSLD, the lack of interior partitions, and the modeling of direct solar radiation on the floor.

Table 6.9 Annual Heating Hours Calculated for 1200 Ft^2 House in Selected Cities with Night Setback[a]

City	Heating Hours				
	House Variation				
	H0	H3	H4	H10	H15
Miami	205	91	89	58	34
Phoenix	2084	1264	1239	879	637
San Antonio	2344	1821	1730	1438	1241
Fort Worth	2665	2133	1977	1580	1335
San Francisco	4925	3452	3055	2032	1345
Sacramento	4156	3076	2878	2260	1831
Atlanta	3181	2615	2411	2006	1761
Washington, D.C.	4301	3849	3553	3110	2803
Seattle	6634	6065	5634	4826	4312
Kansas City	4284	3893	3653	3297	3049
Boston	5288	4941	4598	4197	3912
Chicago	5144	4797	4534	4158	3880
Madison	5678	N/A	5101	4720	4448
Minneapolis	5492	5264	5060	4766	4593

[a] Based on NBSLD analysis, TRY weather data, and the operational profile outlined in section 4.1.

Table 6.10 Annual Cooling Hours Calculated for 1200 Ft^2 House in Selected Cities[a]

City	Cooling Hours — House Variation	
	H0	H3 - H15
Miami	4040	4050
Phoenix	3136	3140
San Antonio	2477	2478
Fort Worth	2374	2376
San Francisco	94	94
Sacramento	1104	1104
Atlanta	1102	1102
Washington, D.C.	1322	1323
Seattle	164	164
Kansas City	1455	1459
Boston	507	508
Chicago	605	605
Madison	583	583
Minneapolis	841	841

[a] Based on NBSLD analysis, TRY weather data, and the operational profile outlined in section 4.1.

The relationship between annual heating requirements and maximum hourly heating loads is plotted in figure 6.5, based on the data presented in tables 6.3 and 6.11. The relationships are shown as linear to facilitate plotting of the data. In fact, there tends to be a high degree of linearity between the two variables, with some tendency to jump downward at the point where the floor insulation is added. In addition, for those cities in the lower left corner of the figure, there tends to be some curvature toward the origin. Data for the cities of Seattle, San Francisco, and Boston all lie significantly above the general trend, indicating that the maximum heating loads for those cities are significantly lower than for other cities that have the same annual heating requirements. This is expected since the winter climate in these three cities is moderated by the nearby ocean.

In general, there is a significant, but non-proportional, relationship between maximum heating requirements and annual heating requirements. A reduction in annual heating requirements is accompanied by a less than proportional decrease in maximum heating load. This implies that properly sized heating equipment will have relatively more part-load operating time as the overall envelope becomes better insulated, since the average hourly heating load (even after adjusting for the decrease in the number of heating hours) decreases faster than the maximum heating load. When the part-load operating efficiency of the heating equipment is less than the full-load efficiency, the seasonal performance of the equipment probably will be reduced. As a result, the actual energy savings resulting from the envelope modifications may be somewhat less than proportional to the reduction in heating requirements.

The relationship between annual cooling requirements ($t_o \geq t_i$) and maximum cooling loads is plotted in figure 6.6. Again the relationships are shown as linear although, in fact, there tends to be some kinking at the point where floor insulation is added. From this figure, it can be seen that the ratio of annual cooling requirements to maximum cooling load tends to vary to a much greater extent than does the ratio of annual heating requirements to the maximum heating load.

The general relationship between annual cooling requirements and maximum cooling loads is also significant. A reduction in annual cooling requirements is accompanied by a greater than proportional decrease in design cooling load. This implies that properly-sized cooling equipment will have relatively less part-load operating time as the overall envelope becomes better insulated, especially where mechanical cooling is not used when the outdoor temperature is below the maximum allowable indoor temperature. This reduction in part-load operating time probably will increase the potential for energy savings resulting from the envelope modifications.

6.2.3 Window and Wall Design by Orientation

The expanded output version of the NBSLD program used in this report provides data on the thermal performance of each of the envelope components that contributes to the heating and cooling loads of the prototype house. These data provide calculated heat gains and losses through the inside surface of the envelope during actual heating and cooling hours, integrated over the entire year. Such

Table 6.11 Maximum Heating Loads for Selected Prototype Variations by City (Btu/hr)

CITY	PROTOTYPE VARIATION With Night Setback				
	H0	H3	H4	H10	H15
Miami	19825	10855	10105	7179	5684
Phoenix	26200	14387	13856	10369	8438
San Antonio	32015	19886	18609	14317	12218
Fort Worth	35210	22658	21315	16754	14789
San Francisco	21025	13109	11887	9213	7665
Sacramento	33562	22197	20733	16379	14353
Atlanta	38233	23898	22431	17688	15181
Washington	43417	29439	27525	22100	19498
Seattle	31252	20282	19174	15027	13143
Kansas City	57087	38171	36443	29728	26038
Boston	48421	32816	30647	24684	21769
Chicago	56600	37698	35569	28917	25489
Madison	66725	45350	42743	35133	31192
Minneapolis	76538	53101	49953	41414	37011

Table 6.12 Maximum Cooling Loads for Selected Prototype Variations by City (Btu/hr)

CITY	PROTOTYPE VARIATION				
	H0	H3	H4	H10	H15
Miami	29553	20205	21520	19828	18735
Phoenix	39166	20965	22273	22352	20964
San Antonio	29192	18236	19601	17647	16495
Fort Worth	34952	19216	21080	18818	17325
San Francisco	20022	12366	16519	15137	13920
Sacramento	33426	16848	17324	15601	14321
Atlanta	30423	15601	18418	16359	14832
Washington	31089	15838	16687	14603	13217
Seattle	25029	13946	15362	13293	11908
Kansas City	29243	18703	19535	17671	16519
Boston	21456	14979	16127	14506	13517
Chicago	29849	16295	17805	15703	14343
Madison	24451	16100	16802	14854	13714
Minneapolis	23773	18432	19387	15190	14037

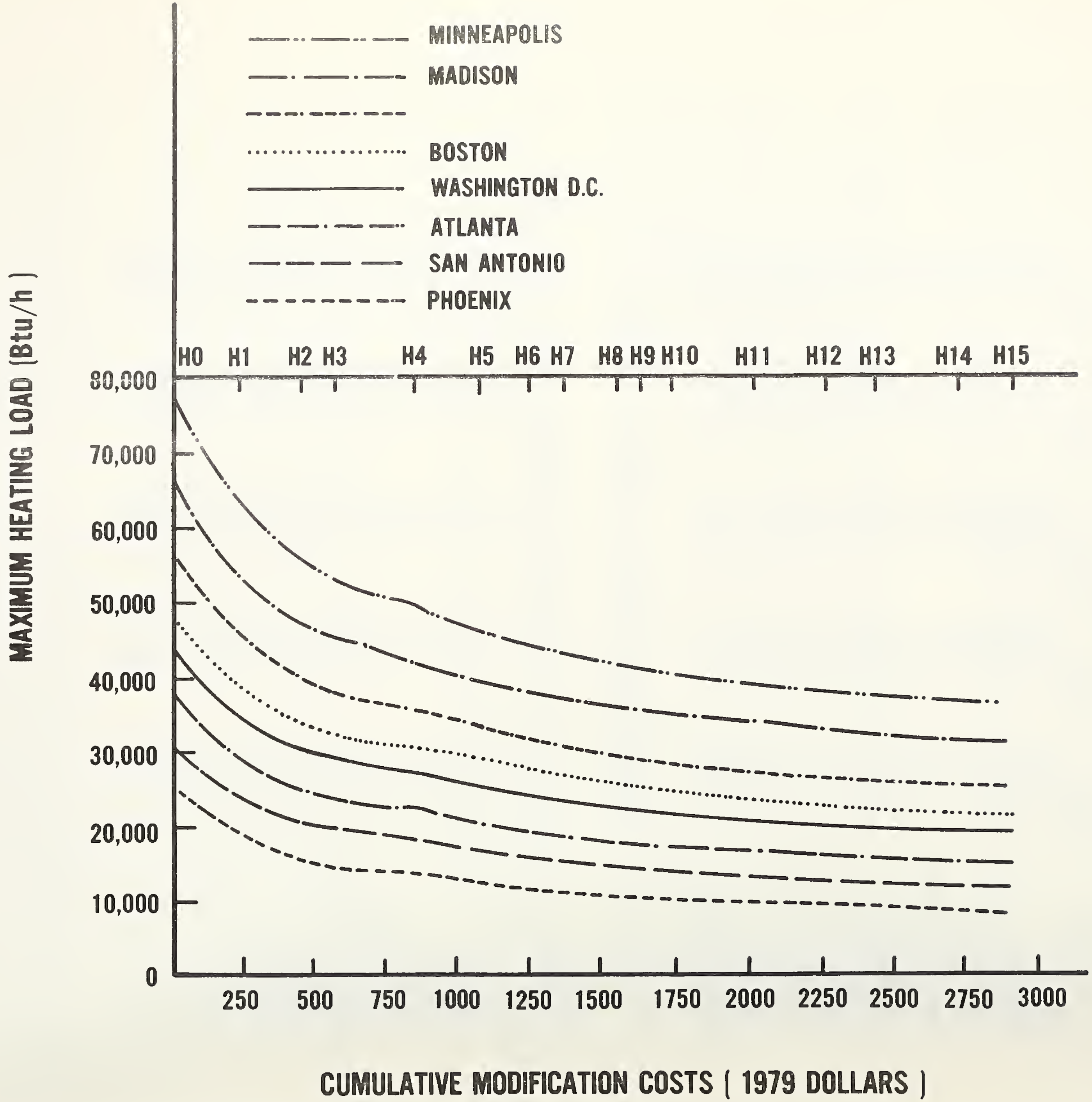

Figure 6.3 Maximum heating load as reduced by energy conserving modifications in selected cities (with night setback)

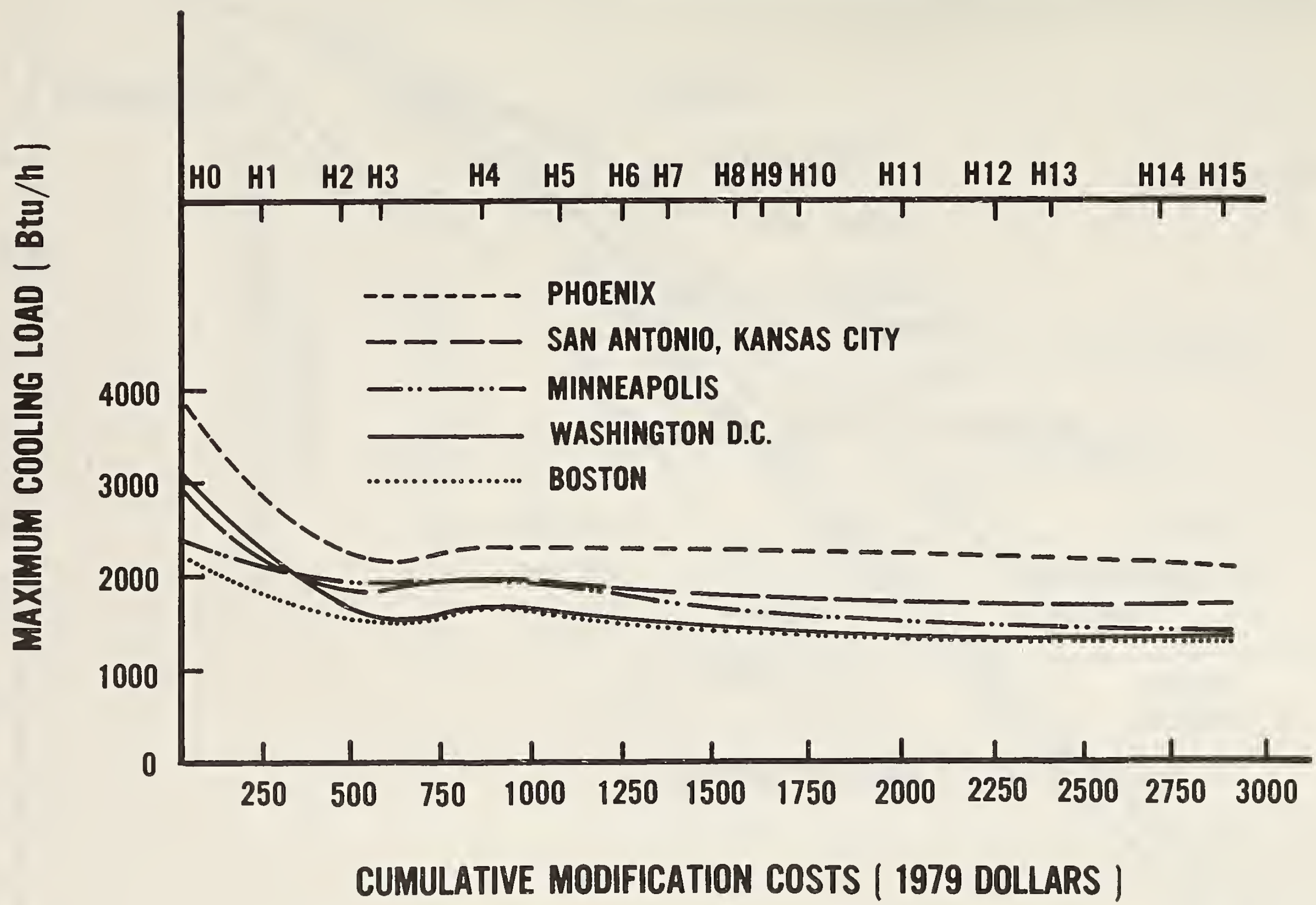

Figure 6.4 Maximum cooling load as reduced by energy conserving modifications in selected cities

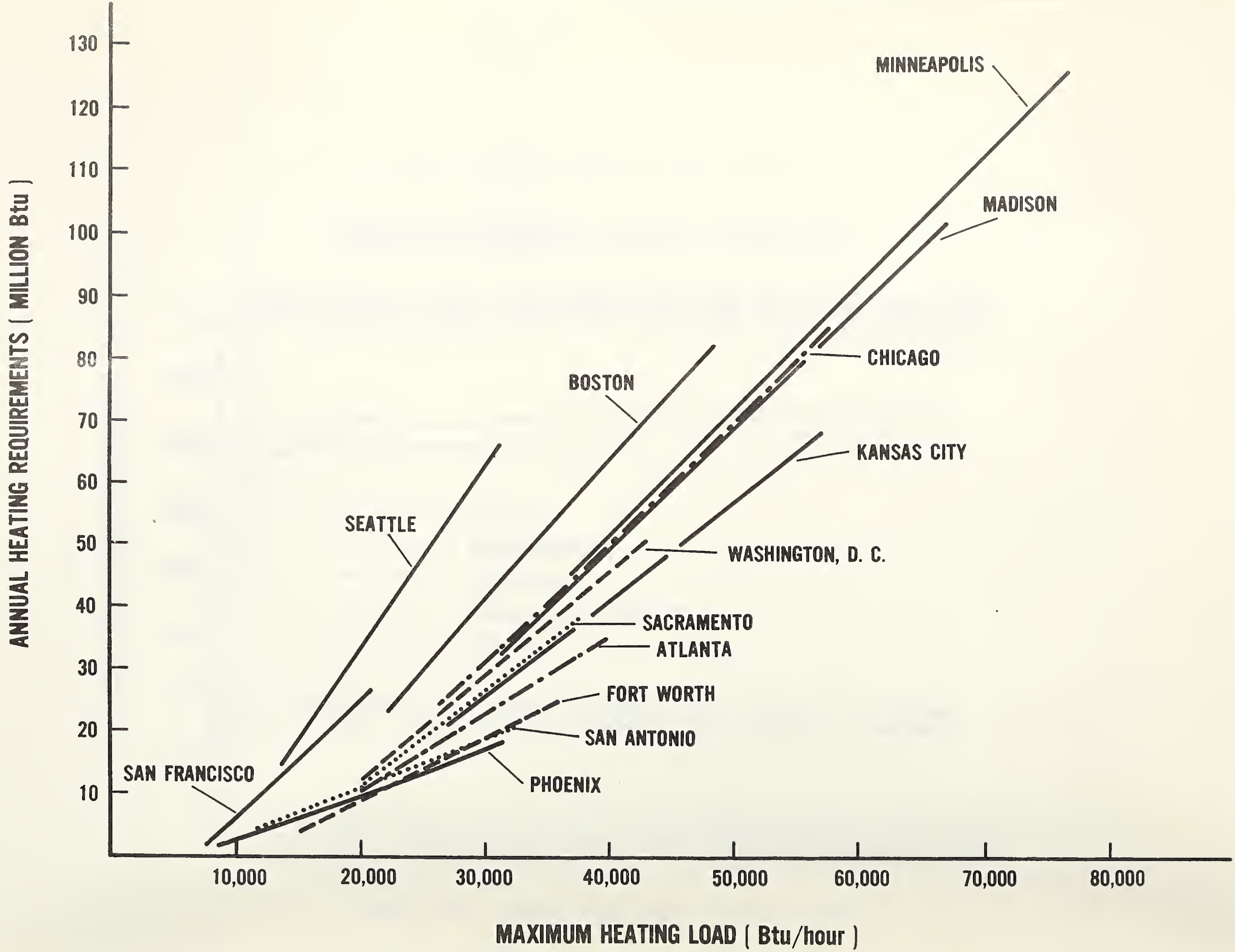

Figure 6.5 Annual heating requirements as a function of maximum heating loads (1200 ft^2 house)

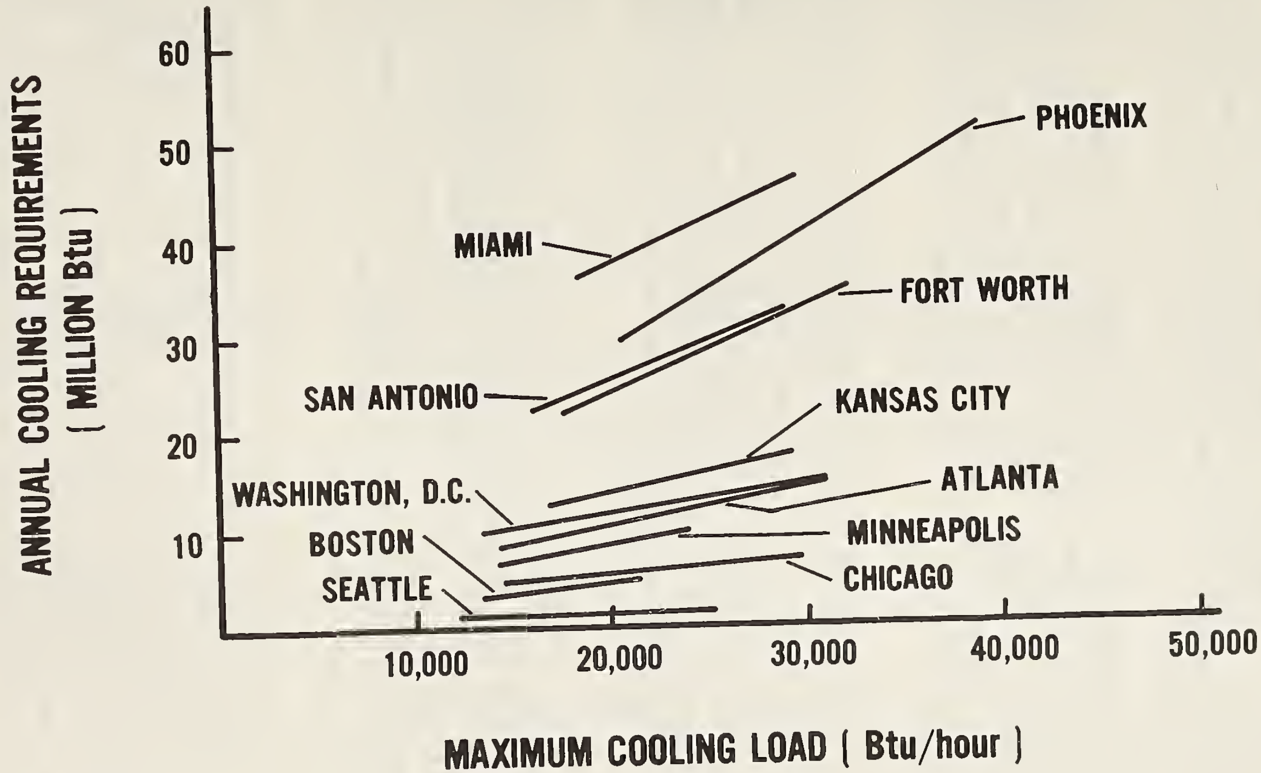

Figure 6.6 Annual cooling requirements as a function of maximum cooling loads (1200 ft^2 house)

information is useful in the envelope design process, especially with respect to making choices between wall and window area and between north and south wall exposures vis-a-vis east and west wall exposures. The usefulness of this component performance data is somewhat limited because of the small internal mass simulated by the NBSLD program. Nevertheless, the resulting data can provide some insight into the thermal processes occurring during the heating and cooling periods of small buildings.

Tables 6.13 and 6.14 provide data from the NBSLD calculations on the conductive heat losses, solar gains, and the ratio of gains to losses through south-facing glass integrated over all heating load hours. For those cases in which the heat gain-to-loss ratio is greater than one, it may be assumed that an increase in the area of south-facing windows will result in a reduction in annual heating requirements. The effects of smaller and larger south-facing window areas will be discussed below.

The window heat loss and heat gain data shown in table 6.13 were calculated for the H4 house, which included R-19 attic, R-11 wall and R-11 floor insulation and single glazing throughout. In all cases, Btu losses during actual heating hours are substantially greater than Btu gains, indicating that larger windows on the southern exposure without a corresponding reduction in window area on the other exposures would tend to increase heating loads unless the thermal storage capacity of the interior was increased substantially to benefit from excess heat in hours when no load exists.

Table 6.14 provides the conductive heat losses and solar gains through south-facing windows in the H10 house. The H10 house includes R-38 attic, R-11 wall, and R-19 floor insulation, and has double glazing throughout. In this case, the ratios indicate that larger, south-facing double-glazed windows can reduce heating requirements in the majority of locations, especially in the colder climates where a greater proportion of total heating hours occur during daylight. Even greater reductions could be expected if the house had a substantial thermal storage capacity.

Table 6.15 provides the annual heating requirements for the same (H10) house modified with 25 percent smaller and 25 percent larger south-facing glass areas. There is a good correlation between changes in heating requirements and the corresponding ratio of gains to losses from table 6.15. It appears that a 25 percent increase in south-facing window area would reduce heating requirements if the ratio of gains to losses is greater than about 1.05. This indicates that not all of the solar gain is useful in offsetting conductive heat losses through the window; some of the beneficial effects of solar gains may be partially offset by an increase in conductive heat losses through the other envelope components.

Tables 6.13-6.15 were calculated based on the assumption that the thermostat was set back 8°F at night to 60°F. When the thermostat is not set back, substantially more heat loss will occur during the night hours, reducing the gain-to-loss ratio below unity in most cases.

Table 6.13 Annual South-Facing Window[a] Heat Transfer (1000 Btu/ft^2) During Heating Load Hours: House H4

City	Conduction Loss	Solar Gain	Gain/Loss
Miami	1.6	1.0	0.60
Phoenix	23.5	9.3	0.40
San Antonio	39.5	25.2	0.64
Fort Worth	46.8	33.6	0.72
San Francisco	51.3	22.0	0.43
Sacramento	56.4	32.0	0.57
Atlanta	61.2	46.5	0.76
Washington	89.2	62.0	0.69
Seattle	124.4	71.8	0.58
Kansas City	116.4	85.0	0.73
Boston	141.3	111.4	0.79
Chicago	140.4	98.8	0.70
Madison	168.5	109.5	0.65
Minneapolis	199.1	125.7	0.63

[a] Window U = 1.13, shading coefficient = 0.8.

Table 6.14 Annual South-Facing Window[a] Heat Transfer (1000 Btu/ft^2) During Heating Load Hours: House H10

City	Conduction Loss	Solar Gain	Gain/Loss
Miami	0.6	0.7	1.05
Phoenix	9.8	5.6	0.57
San Antonio	17.9	17.7	0.99
Fort Worth	20.6	20.7	1.00
San Francisco	18.8	9.9	0.53
Sacramento	25.7	21.1	0.82
Atlanta	27.9	30.2	1.08
Washington	43.2	44.1	1.02
Seattle	58.6	51.5	0.88
Kansas City	57.6	65.3	1.14
Boston	68.0	84.8	1.25
Chicago	70.2	77.5	1.10
Madison	85.6	86.9	1.01
Minneapolis	101.2	101.2	1.00

[a] Window U = 0.56, shading coefficient = 0.7.

Table 6.15 Effect of Change in South-Facing Glass Area on Annual Heating Requirements: House H10[a]

City	Annual Heating Requirements (Million Btu) Change in Glass Area -25%	0	+25%	Gain-loss ratio for base house[b]
Miami	0.128	0.129	0.131	1.05
Phoenix	2.365	2.445	2.546	0.57
San Antonio	5.206	5.207	5.240	0.99
Fort Worth	6.335	6.265	6.277	1.00
San Francisco	3.622	3.714	3.868	0.53
Sacramento	6.879	6.922	7.021	0.82
Atlanta	9.212	9.102	9.080	1.08
Washington, DC	15.649	15.570	15.574	1.02
Seattle	19.201	19.272	19.430	0.88
Kansas City	25.142	24.965	24.887	1.14
Boston	29.875	29.503	29.231	1.25
Chicago	29.736	29.575	29.505	1.10
Minneapolis	53.836	53.830	53.902	1.00

a Base design has 72 ft^2 of south-facing glass.

b From table 6.16.

Table 6.16 Annual South-Facing Window[a] Heat Transfer (1000 Btu/ft^2) During Cooling Hours: House H10

City	Conduction Gain	Solar Gain	Total Gain
Miami	4.3	62.3	66.6
Phoenix	14.4	61.3	75.7
San Antonio	6.5	34.4	40.9
Fort Worth	5.9	39.4	45.3
San Francisco	0.0	4.3	4.3
Sacramento	3.0	26.8	29.8
Atlanta	0.9	19.7	20.6
Washington	2.5	18.1	20.6
Seattle	0.3	3.7	4.0
Kansas City	3.0	23.5	26.5
Boston	0.8	9.6	10.4
Chicago	0.9	11.5	12.4
Madison	0.7	9.5	10.2
Minneapolis	1.6	16.8	18.4

[a] Window U = 0.56, shading coefficient = 0.35.

Increasing the area of south-facing windows may also affect cooling requirements, and these effects must be considered before such a design change is adopted. Table 6.16 provides the annual conduction and solar gains per square foot of south-facing glass area during cooling hours for the H10 house (U = 0.56, shading coefficient = 0.35). These data can be adjusted to reflect other effective shading coefficients and U-values to compute the effects of south-facing window modifications on annual cooling requirements. Increased solar gains during cooling hours may partially offset or completely negate the advantages of larger south-facing windows during the heating season. Therefore, the net dollar savings in combined heating and cooling costs must be computed in order to determine whether larger or smaller windows are desirable from an economic standpoint.

In addition to the above discussion regarding window sizing, these factors should also be considered:

(1) All the above calculations were made based on the assumption that windows were not covered nor otherwise modified at night. Selective window management, such as insulated shutters, drapes, or shades, used at night to reduce conductive heat losses, would likely make south-facing windows more beneficial in terms of net gains during heating hours.[1]

(2) The calculations assume that solar gains through windows are circulated to offset potential or real heating loads in any part of the house. This prevents the overheating of rooms on the south exposure while heating is required in rooms on the north exposure. If solar gains are not circulated, they may not be as useful as assumed in this analysis.

(3) The data in tables 6.13 through 6.16 are based on TRY climate records for the years indicated in table 6.1, which may not be good long-term indicators of specific climate parameters such as cloud cover and actual solar gain.

(4) This report examined south-facing windows only because they are the ones most likely to provide net thermal benefits during the heating season. Since the benefits of increased south-facing windows were marginal at best, it is reasonable to conclude that increases in east-, west-, or north-facing windows will increase annual heating requirements. Moreover, the solar gains on the east and west exposures during cooling hours will likely result in a further decrease in the net annual thermal performance of windows oriented in those directions.

(5) This report does not consider the beneficial aspects of windows other than their thermal performance. Factors such as aesthetics (for example, an appealing view) and the possible advantages of daylighting

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[1] See S. R. Hastings, Window Design Strategies to Conserve Energy.

resulting from larger windows should be considered before deciding on the optimal window size.[1]

Component performance data can also be useful in determining the effects of wall orientation in the building design process. Table 6.17 shows that the ratio of total heat loss on the east and west exposures to the total heat loss on the north and south exposures (normalized by area) is nearly unity for each location examined. This implies that any change in building orientation (while leaving window orientation and size unchanged) would have little or no effect on annual heating requirements. (Only the H10 variation is shown because the relative effects of wall orientation are not significantly changed as the envelope insulation is increased. The prototype house examined is oriented with the longer walls (40 ft) facing north and south and the shorter walls (30 ft) facing east and west. It appears that a square-shaped house (34.64 ft on each side) having the same floor space (1200 ft^2) with minimum possible wall area (1108.5 ft^2 instead of 1120 ft^2) would be optimal in terms of reduced heating requirements since the benefits from longer north and south facing walls are insignificant.

Table 6.17 also shows the ratio of north wall heat loss to south wall heat loss. The data suggest that significantly more heat is lost from the north wall relative to the south wall during heating hours, which may justify the use of more insulation in the north wall. On the other hand, heat loss through the east and west walls during heating load hours appears to be nearly identical in all cases.

Table 6.18 shows wall heat gains by orientation during cooling load hours when the outdoor temperature is greater than 78°F. During these cooling load hours, the total heat gain per unit area is significantly greater for the east and west wall exposures than for the north and south exposures in all locations except San Francisco. (San Francisco has almost no annual cooling requirements.) In addition, any sizable roof overhang on the south side would reduce heat gains through that wall even further. Thus, in the majority of cases, the additional heat gain on the east and west walls is high enough to warrant (from a cooling requirement standpoint) somewhat longer walls on the north and south exposures and correspondingly shorter walls on the east and west exposures, even if this increases total wall area slightly for a given floor area. However, practical design and living considerations and the increase in total wall area will likely limit the extent to which an increase in the NS/EW ratio will reduce annual cooling requirements.

In determining the optimal wall configuration for a house with respect to shape and orientation, it appears that total surface area is the primary consideration for heating requirements, while a significant bias towards longer walls on the north and south exposure is warranted for cooling. Thus, the selection of shape depends largely on whether heating or cooling costs dominate, while selection of major orientation generally favors north and south exposures unless there are no cooling requirements at all.

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[1] See T. Kusuda and B. Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, BSS 109, National Bureau of Standards, Washington, D.C., 1978.

Although the lot size, shape, and orientation will usually dictate the size, shape, and orientation of a house, orientation can still be an important design consideration. The shape of the envelope itself may be somewhat restricted, but the orientation and size of the windows and the location of the daytime activity centers within (i.e., kitchen, dining and family room) close to the sources of solar and internal heat gains in winter can have a significant effect on the energy requirements for space heating and daylighting.

6.2.4 Relative Sources of Envelope Heat Loss and Heat Gain

The expanded version of the NBSLD computer program allows the user to identify the sources of heat loss and heat gain that make up annual heating and cooling requirements. Such data may be of considerable interest to the designer. However, the space available to report these sources is limited and thus only a brief summary is presented.

Table 6.19 shows the relative sources of envelope heat loss during hours when heating loads exist. Data are shown for three cities -- San Antonio (mild winter; warm summer), Washington, D.C. (moderate winter and summer), and Minneapolis (severe winter, mild summer) -- and for four versions of the prototype house -- H0, H4, H10, and H15 -- to demonstrate how the relative make-up of heating and cooling requirements change as the thermal conductance of the various envelope components is reduced.

It is interesting to note that as the envelope is upgraded, infiltration losses rise from less than one-quarter to more than one-half of the total loss. (The rate of infiltrations is not changed in the analysis.)

Table 6.20 shows the relative sources of envelope heat gain during hours when cooling loads ($t_o \geq t_i$) exist for the same locations and house variations. Both conductive and radiative heat gains are considered, as well as internal loads from lights, equipment and people. (The floor is excluded here because it is not a source of heat gain but instead acts as a heat sink.) Solar gains and internal loads together make up about 40 percent of the annual cooling requirements in the uninsulated house (H0) and about 55 to 65 percent of the annual cooling requirements in the superinsulated house (H15).

Table 6.21 provides the annual latent cooling requirements ($t_o \geq t_i$) corresponding to the total annual cooling requirements of table 6.6. (These are needed in order to compute the sensible cooling requirements that are discussed in section 7.) These latent cooling requirements remain virtually constant as the envelope modifications are made because the number of cooling hours ($t_o \geq t_i$) remains constant.

6.2.5 Effect of House Size on Component Performance

The effects of envelope size on component performance and the corresponding design considerations were not explicitly calculated in this report. However, since envelope heat losses and gains are approximately proportional to the surface area of the envelope components, weighted by the component U-values, one can expect heating and cooling requirements per square foot of floor area to

Table 6.17 Annual Wall Heat Losses During Heating Hours (1000 Btu/ft^2): House H10 With Night Setback

City	N+S	E+W	E+W/N+S	N/S	E/W
Washington	10.73	10.77	1.00	1.21	1.00
San Antonio	4.42	4.38	0.99	1.15	0.98
Sacramento	6.32	6.41	1.01	1.25	0.96
Phoenix	2.38	2.33	0.98	1.14	0.99
Minneapolis	25.31	25.52	1.01	1.17	0.99
Fort Worth	4.89	4.81	0.98	1.19	0.99
Chicago	17.12	17.30	1.01	1.22	0.99
Boston	16.33	16.45	1.01	1.19	1.01
Atlanta	6.79	6.56	0.97	1.13	1.00
Seattle	14.98	15.02	1.00	1.17	0.99
Miami	0.18	0.18	0.96	1.09	1.00
Kansas City	13.97	14.12	1.01	1.21	0.99
San Francisco	4.33	4.11	0.97	1.20	1.94
Madison	21.19	81.35	1.01	1.20	0.99

Table 6.18 Annual Wall Heat Gains During Cooling Hours (1000 Btu/ft^2): House H10

City	N+S	E+W	E+W/N+S	N/S	E/W
Washington	1.71	2.47	1.45	0.52	1.05
San Antonio	3.21	4.48	1.40	0.64	0.97
Sacramento	2.44	3.11	1.28	0.45	0.98
Phoenix	7.93	10.20	1.29	0.59	1.06
Minneapolis	1.08	1.49	1.38	0.39	0.99
Fort Worth	3.58	4.83	1.36	0.61	1.11
Chicago	0.76	1.04	1.37	0.39	1.09
Boston	0.51	0.67	1.31	0.40	1.01
Atlanta	1.35	2.22	1.64	0.43	1.08
Seattle	0.28	0.37	1.30	0.37	0.88
Miami	3.40	4.79	1.41	0.56	1.20
Kansas City	1.99	2.70	1.35	0.51	0.97
San Francisco	0.17	0.17	0.98	0.45	0.86
Madison	0.79	1.01	1.35	0.14	1.00

Table 6.19 Relative Sources of Heat Loss During Heating Hours

COMPONENT (ft^2)	Percent of Total Heat Loss			
San Antonio	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	37.1	9.8	7.6	6.9
Walls (972.9)	20.5	24.3	17.8	14.8
Glass (127.1)[1]	16.1	26.2	19.3	16.6
Door (20)	1.1	1.8	2.6	2.0
Floor (1200)	2.3	4.9	5.6	6.7
Infiltration	22.9	33.0	47.1	53.0
Total	100 %	100 %	100 %	100 %

Washington, D.C.	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	33.0	10.5	7.2	6.7
Walls (972.9)	19.7	14.0	17.6	11.8
Glass (129.1)[1]	14.7	27.2	17.9	15.9
Door (20)	1.0	1.9	2.4	1.9
Floor (1200)	8.5	9.4	8.9	10.6
Infiltration	22.9	37.0	45.9	53.1
Total	100 %	100 %	100.%	100 %

Minneapolis	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	30.3	9.4	6.4	5.8
Walls (972.9)	19.6	13.1	15.3	10.8
Glass (129.1)[1]	14.2	25.2	16.3	14.1
Door (20)	1.0	1.2	2.2	1.6
Floor (1200)	7.8	8.6	8.2	9.5
Infiltration	27.2	42.0	51.7	58.3
Total	100 %	100 %	100 %	100 %

[1] Data for glass losses do not include solar gains.

Table 6.20 Relative Sources of Heat Gain During Cooling Hours ($t_o \geq t_i$)

Component (ft^2)	Percent of Total Heat Gain			
San Antonio	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	25.8	8.8	5.2	4.6
Walls (972.9)	13.7	7.5	7.8	4.7
Glass (127.1)				
Conductive	2.3	5.4	3.5	3.0
Solar	11.1	14.9	14.2	13.9
Door (20)	0.4	0.7	0.8	0.6
Infiltration	19.5	26.3	28.7	30.7
Internal Loads	27.0	36.5	39.8	42.5
Total	100 %	100 %	100 %	100 %

Washington, D.C.	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	31.4	10.8	6.2	5.6
Walls (972.9)	14.8	8.8	13.3	6.8
Glass (127.1)				
Conductive	1.2	4.2	2.8	2.6
Solar	11.6	16.7	15.3	15.6
Door (20)	0.4	0.7	0.8	0.6
Infiltration	12.0	17.4	18.2	20.3
Internal Loads	28.6	41.3	43.3	48.3
Total	100 %	100 %	100 %	100 %

Minneapolis	Prototype Variation			
	H0	H4	H10	H15
Ceiling (1200)	30.3	10.3	5.7	5.4
Walls (972.9)	15.2	8.2	9.0	5.8
Glass (127.1)				
Conductive	1.2	4.0	9.8	2.4
Solar	15.3	22.2	19.6	21.1
Door (20)	0.4	0.7	0.7	0.6
Infiltration	11.4	16.5	16.7	19.6
Internal Loads	26.2	37.9	38.4	45.0
Total	100 %	100 %	100 %	100 %

Table 6.21 Latent Cooling Requirements for All House Variations[a]

City	Latent Cooling Requirements (Million Btu)
Miami	12.257
Phoenix	1.378
San Antonio	5.144
Fort Worth	4.446
San Francisco	0.0
Sacramento	0.0
Atlanta	2.057
Washington, D.C.	1.533
Seattle	0.0
Kansas City	2.804
Boston	0.677
Chicago	0.547
Madison	0.607
Minneapolis	0.913

[a] This table of latent cooling requirements corresponds to the total cooling requirements shown in table 6.6. Note that these latent cooling requirements remain constant as the modifications to the envelope are incorporated.

decrease as the floor space is increased. This is because the building surface-to-volume ratio decreases with increases in floor area. However, heat loss and heat gain per unit surface area, by component, will vary very little, regardless of the house size. This implies that the design guidelines for each component also remain constant.

In fact, the analysis is not as simple as implied here. One critical factor in such an analysis is the number of heating and cooling load hours incurred as a function of the envelope size. Energy savings can only be realized during hours in which there are heating or cooling loads. If the ratio of net envelope heat losses to internal and solar heat gains decreases as the overall house size is increased, the balance point of the house for heating will decrease and the number of heating hours will decrease correspondingly. This will reduce the potential energy savings resulting from any envelope modification as the house size is increased. However, it is not realistic to assume that solar and internal gains will increase proportionally with the square footage of the floor space.

Internal heat gains are most likely a function of family size, with some downward bias as family size grows because of fixed internal heat sources such as pilot lights, lighting, and, to some extent, cooking and refrigeration. Moreover, family size has not been shown to increase proportionally with an increase in floor space in single-family housing.

Thus, an assumption that heating and cooling hours remain relatively constant regardless of house size (within the limits of single-family housing) is not unrealistic. In essence, this would require that solar and internal heat gains increase as a function of the increase in envelope surface area rather than in floor area. Because the number of cooling load hours ($t_o \geq t_i$) remains relatively constant regardless of the overall integrity of the envelope, the savings calculated per square foot of envelope area will remain essentially constant regardless of house size and internal heat release.

Thus, the optimal insulation levels calculated in this report for a 1200 ft^2, one-story house can be generally applied to similar housing regardless of size. However, a two-story house with the same floor area as a one-story house may have fewer heating hours annually because of its more compact nature and, as a result, reductions in heating requirements per square foot of envelope area due to modifications to the building envelope may be slightly less than those calculated for a one-story house. (The heat gains during those marginal heating hours eliminated make up only a small proportion of the total heat gain during the heating seasons.)

7. ADJUSTMENTS FOR CLIMATE VARIATIONS

7.1 INTERPOLATION OF ANNUAL HEATING AND COOLING REQUIREMENTS

The 14 locations used in this report have heating and cooling seasons representative of the wide range of climates in the continental United States. However, the ability to estimate annual heating and cooling requirements in other locations and for better representations of long-term climatic conditions in the 14-city sample is quite important. Even more important here is the ability to estimate the effects of conservation measures in reducing annual heating and cooling requirements throughout the United States. Heating and cooling degree day data have often been used for both these purposes, especially for residential buildings. This section examines the usefulness of this degree day data for interpolating heating and cooling requirements for other climates based on NBSLD analysis for the 14 locations discussed in section 6.

Linear regression analysis was used to determine the best relationship (in a least-squares sense) between annual heating and cooling requirements and annual heating and cooling degree days (HDD and CDD), calculated at different base temperatures. In addition, annual cooling requirements were correlated with annual cooling degree hours (CDH) to determine whether a better estimator of cooling requirements could be found.

Traditionally, heating and cooling degree days have been calculated using a base temperature of 65°F. However, as explained in section 3, the appropriate balance point at which space heating or cooling is required is likely to change as the building becomes better insulated, or tighter from a thermal performance standpoint. This is especially true for heating requirements, since solar gains and internal heat generation are able to offset a greater percentage of the heat losses as the envelope becomes better insulated. Thus, the appropriate base temperature for calculating heating degree days falls as the building becomes better insulated or as internal or solar gains are increased.

Table 7.1 provides HDD data computed from the Test Reference Year (TRY) tapes used in the NBSLD analysis for the 14 cities. These data are calculated for base temperatures decreasing at 2.5°F intervals from 65° to 42.5°F. A number of linear regression analyses were run for the 14 cities to determine which degree day base provided the best correlation between TRY heating degree days and the annual heating requirements calculated in section 6. The results of those analyses are shown in table 7.2. The best-fit heating-degree-day base ranged from 57.5°F for the uninsulated house to 50.0°F for the superinsulated (H15) house. The rate of infiltration, solar gain, and internal heat generation are constant in all cases. Thus, the change in balance point is due entirely to the reduction in the rate of conductive heat loss through the building envelope.

While the H0 (uninsulated) house balance point of 57.5°F is significantly lower than the base 65°F traditionally used, it must be remembered that the indoor temperature during heating periods was kept at 68°F during the waking hours and 60°F during sleeping hours, substantially below the 70°-75°F daily range that was common at the time when the 65°F base was established. Moreover, the

Table 7.1 TRY Heating Degree Days to Selected Bases

Heating Degree Day Base (°F)

City	65.0	62.5	60.0	57.5	55.0
Miami	130	79	48	27	15
Phoenix	1571	1193	963	607	404
San Antonio	1897	1562	1257	994	758
Fort Worth	2373	1983	1636	1327	1048
San Francisco	3557	2702	1930	1300	813
Sacramento	3144	2578	2072	1627	1243
Atlanta	2959	2500	2080	1698	1370
Washington, DC	4161	3616	3106	2629	2184
Seattle	5562	4738	3944	3211	2553
Kansas City	5058	4507	4007	3541	3114
Boston	5781	5129	4524	3956	3441
Chicago	6103	5451	4852	4292	3768
Madison	7311	6611	5952	5341	4765
Minneapolis	8316	7689	7083	6500	5934

City	52.5	50.0	47.5	45.0	42.5
Miami	9	4	2	0	0
Phoenix	258	150	69	28	6
San Antonio	558	383	245	138	69
Fort Worth	793	563	373	228	129
San Francisco	440	206	90	37	10
Sacramento	922	649	436	277	164
Atlanta	1078	821	600	417	273
Washington, DC	1785	1428	1111	827	590
Seattle	1984	1494	1071	719	461
Kansas City	2709	2342	2004	1695	1409
Boston	2958	2524	2123	1743	1402
Chicago	3283	2834	2414	2014	1640
Madison	4230	3735	3263	2810	2391
Minneapolis	5391	4875	4395	3938	3496

Table 7.2 Best Linear Regression Results: Heating Degree Days and Annual Heating Requirements

House Variation	HDD Base	Regression Equation Constant	Regression Equation Slope	R^2	Standard Deviation of Residuals
H0	57.5°F	1.065	0.0192	0.997	1.85
H4	55.0°F	-1.488	0.0193	0.996	1.33
H10	52.5°F	-0.956	0.0098	0.995	1.06
H15	50.0°F	-0.350	0.0091	0.995	0.93

prototype house has less leakage due to air infiltration than most existing houses. Window areas for the prototype are also somewhat less than average.

Figure 7.1 shows the HDD data for both base 65°F and 55°F (HDD_{65} and HDD_{55}) and the corresponding annual heating requirements of the H4 envelope variation (R-19 attic, R-11 wall and R-11 floor insulation, single glazing) for the 14 cities. The heating requirements fall noticeably closer to the HDD_{55} regression line than the HDD_{65} line. Moreover, the HDD_{55} regression line is much closer to the zero intercept, making it a much better predictor of annual heating requirements in milder climates such as San Francisco and Miami. This high degree of correlation implies that HDD data can be used with some confidence to interpolate annual heating requirements for other climates, provided that the appropriate degree day base is known. Degree day data for a wide range of calculation bases can be obtained from the National Climatic Center.[1] Maps of the United States showing heating degree days calculated at four different bases are provided in appendix D.

In contrast to the acceptance of heating degree days as an aid for calculating annual heating requirements, cooling degree days (CDD) have not been as generally accepted for calculating annual cooling requirements. The most important reason for the lack of acceptance is that CDD do not adequately reflect the differences in solar gains and internal heat generation from house to house, which together make up a substantial portion of the total cooling load. In addition, CDD do not reflect the range of daily temperature variation nor the magnitude of the latent cooling load.

Although the usefulness of CDD is limited, they may serve as a reasonable basis for interpolating cooling energy requirements for the same house operated in the same manner between locations with known cooling requirements and CDD. Moreover, if only sensible cooling requirements are to be estimated, one would expect a higher estimating reliability because the poor correlation between wet bulb temperatures and CDD is avoided. Sensible cooling requirements can be calculated by subtracting the latent cooling requirements reported in table 6.21 from the total cooling requirements reported in table 6.6.

Table 7.3 provides CDD data calculated from the TRY tapes used in the NBSLD analyses for the 14 cities. The CDD data are calculated at 2.5°F intervals from 65° to 80°F. Several linear regressions were made for the 14 cities to determine which temperature base best correlated CDD with annual sensible cooling requirements ($t_o \geq t_i$). The results of those analyses are shown in table 7.4.

Figure 7.2 shows a plot of the CDD data at bases 65° and 72.5°F and the corresponding sensible cooling loads ($t_o \geq t_i$) for the H4 house in the 14 cities. Although the overall fit is good for the CDD base 72.5°F data, there is still considerable variation from the regression line, especially for

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[1] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, "Degree Days to Selected Bases," Ashville, N.C. 28801, (no date).

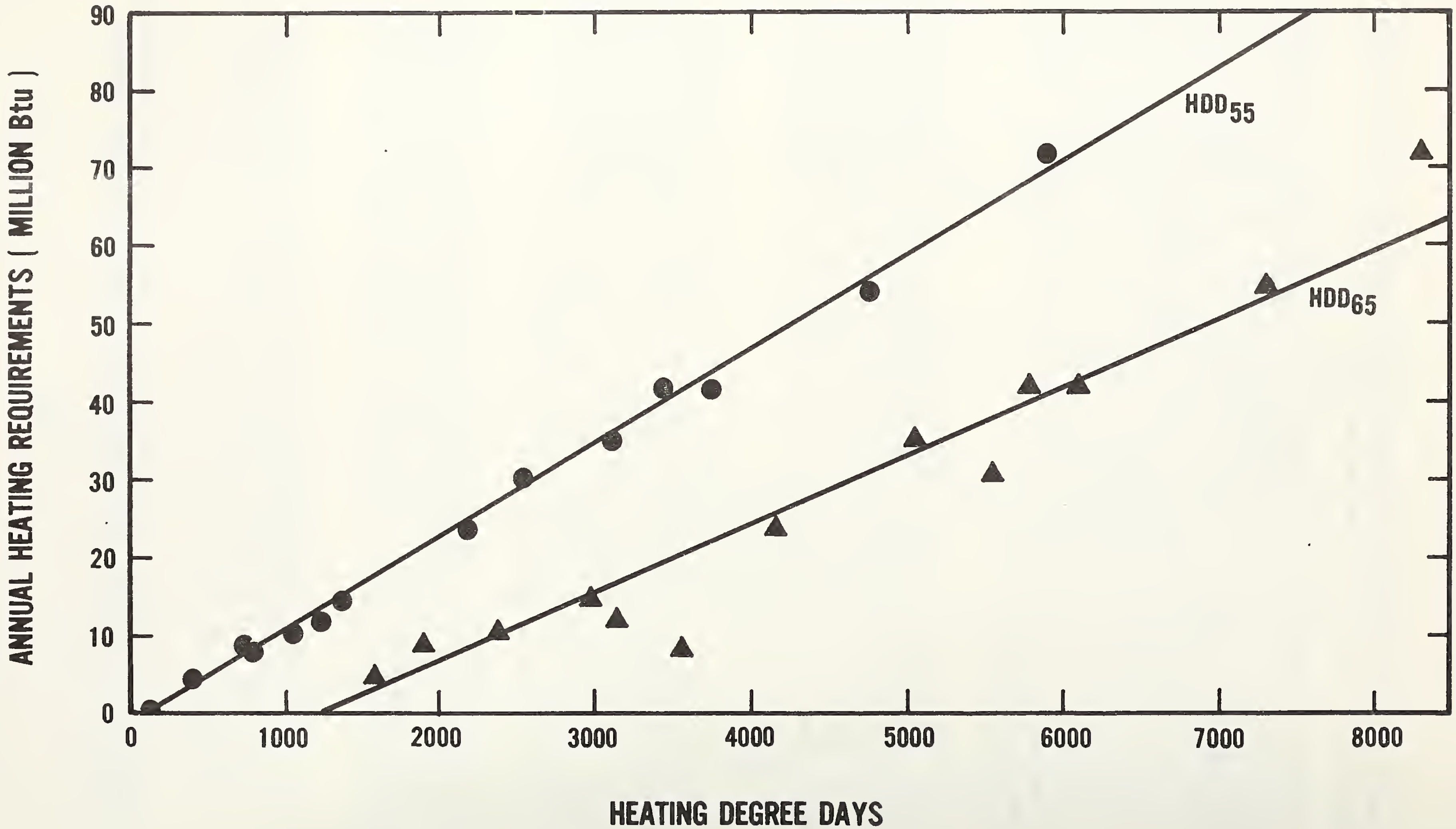

Figure 7.1 Annual heating requirements as a function of HDD_{65} and HDD_{55} (H4 house)

Table 7.3 TRY Cooling Degree Days to Selected Bases

City	65.0	67.5	70.0	72.5	75.0	77.5	80.0
	Cooling Degree Day Base (°F)						
Miami	4176	3333	2522	1769	1117	615	283
Phoenix	3434	2934	2471	2037	1651	1293	968
San Antonio	2739	2195	1708	1265	877	545	286
Fort Worth	2495	2014	1580	1194	962	575	332
San Francisco	35	13	4	1	0	0	0
Sacramento	779	504	298	161	77	32	12
Atlanta	1359	956	614	324	132	34	2
Washington, D.C.	1482	1142	830	566	344	174	72
Seattle	143	95	59	31	15	7	3
Kansas City	1485	1154	868	628	421	259	133
Boston	667	467	310	193	104	45	15
Chicago	731	507	319	186	99	49	23
Madison	454	285	165	92	55	29	11
Minneapolis	919	658	451	282	156	73	28

Table 7.4 Best Linear Regression Results: Cooling Degree Days and Annual Sensible Cooling Requirements

House Variation	CDD Base	Regression Equation: Constant	Regression Equation: Slope	R^2	Standard Deviation of Residuals
H0	75°F	4.57	0.0268	0.941	3.28
H4	72.5°F	2.405	0.0151	0.959	2.03
H10	72.5°F	2.214	0.0136	0.964	1.69
H15	72.5°F	1.91	0.0125	0.969	1.44

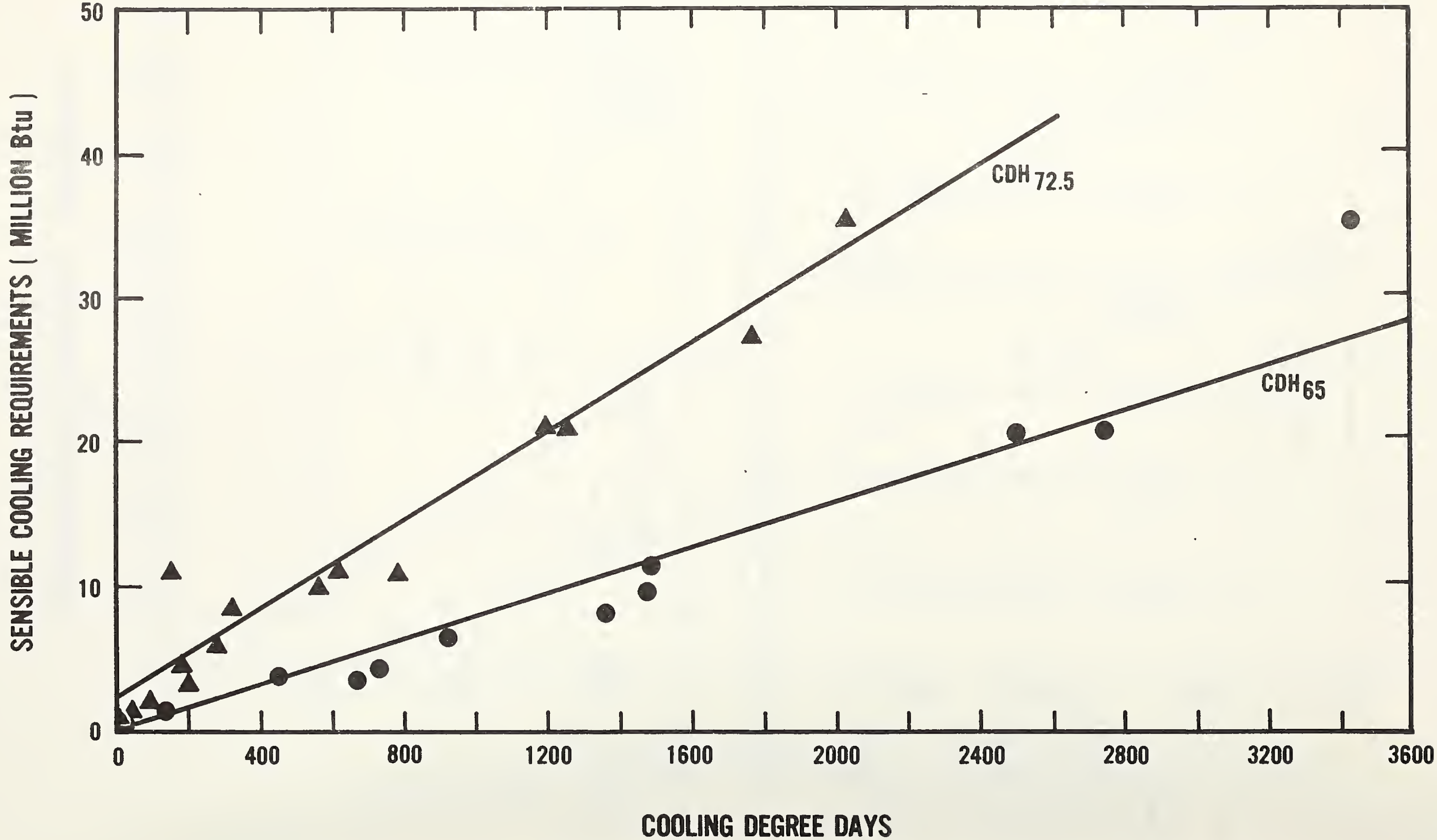

Figure 7.2 Annual sensible cooling requirements as a function of CDD_{65} and $CDD_{72.5}$ (H4 house)

Sacramento, a city with a relatively high daily temperature range in the summer. Note also that the $CDD_{72.5}$ line does not pass as close to the zero intercept as does the CDD_{65} line.

An alternative approach to CDD for interpolation purposes is to use cooling degree hours (CDH) calculated from the TRY tapes used in the NBSLD analysis. This has the advantage of representing average hourly data rather than average daily data, which would likely be more accurate where the variation in daily temperature is significant. Table 7.5 provides CDH data as calculated from the TRY tapes. The CDH data are calculated at 2.5°F intervals from 65° to 80°F.

Several linear regressions were made for the 14 cities to determine which calculation base best correlated CDH with annual sensible cooling requirements ($t_o \geq t_i$). The results of those analyses are shown in table 7.6. These results are significantly better than those for the CDD data, although the best-fit CDH calculation bases are the same as those for CDD. The coefficient of determination (R^2) is close to 1.0 and the standard deviation of the residuals is low relative to that for the CDD analysis. Figure 7.3 provides a plot of the CDH data base 65°F and base 72.5°F and the corresponding sensible cooling loads ($t_o \geq t_i$) for the H4 house in 14 cities.

It appears that CDH data can provide a reliable basis for interpolating sensible cooling requirements, provided that the envelope design and orientation, infiltration rate, and internal heat gains are held constant. While CDH data are not as readily available as CDD data, they can be calculated from "bin" data which are available for a large number of cities from the National Climatic Center.[1]

Latent cooling requirements correlate poorly with CDD and CDH data and therefore must be estimated separately. However, sensible cooling load data are sufficient for the analysis of changes to the building envelope which modify conductive and solar heat gains. These modifications will have little or no effect on latent cooling loads, since the number of cooling load hours ($t_o \geq t_i$) and infiltration rates remain virtually constant at all levels of thermal integrity.

7.2 INTERPOLATION OF CHANGES IN ANNUAL HEATING AND COOLING REQUIREMNTS

The use of degree day and degree hour data for interpolating heating and cooling requirements for locations other than the 14 TRY locations examined greatly extends the value of the data presented in section 6. However, it is necessary to estimate the reduction in heating and cooling requirements resulting from envelope modifications (rather than the requirements themselves) to provide quantitative data for economic analysis. Since the balance point may change as

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[1] Data for individual cities are published in "Summary of Hourly Observations" available from the National Climatic Center, Asheville, N.C. 28801. A summary of bin data for approximately 140 cities is also available from the same source, although in unpublished form. The methodology used in this report for calculating cooling degree hours data from bin data is reported in appendix C.

Table 7.5 TRY Cooling Degree Hours to Selected Bases

City	65.0	67.5	70.0	72.5	75.0	77.5	80.0
	Cooling Degree Hour Base (°F)						
Miami	101655	81754	62806	45535	30348	18559	9975
Phoenix	90743	78429	67138	56960	47746	39474	32065
San Antonio	69687	56831	45088	34806	25979	18949	13476
Fort Worth	64527	53053	42427	32980	24761	18141	12853
San Francisco	4357	2726	1659	1059	682	416	214
Sacramento	31104	25295	20332	16188	12632	9639	7114
Atlanta	36104	26632	18665	12722	8264	5075	2694
Washington, D.C.	37585	29680	22729	16826	12025	9328	5381
Seattle	6482	4707	3348	2326	1575	1051	686
Kansas City	39554	31575	24577	18601	13546	9493	6277
Boston	18260	13363	9452	6458	4222	2716	1656
Chicago	20776	15418	11027	7669	5124	3292	2047
Madison	15911	11668	8330	5851	3934	2485	1458
Minneapolis	25397	19679	14721	10801	7654	5254	3406

Table 7.6 Best Linear Regression Results: Cooling Degree Hours and Annual Sensible Cooling Requirements

House Variation	CDH Base	Regression Equation		R^2	Standard Deviation of Residuals
		Constant	Slope		
H0	75°F	1.133	1.04×10^{-3}	0.993	1.15
H4	72.5°F	0.146	0.609×10^{-3}	0.998	0.49
H10	72.5°F	0.210	0.546×10^{-3}	0.998	0.36
H15	72.5°F	0.090	0.501×10^{-3}	0.998	0.36

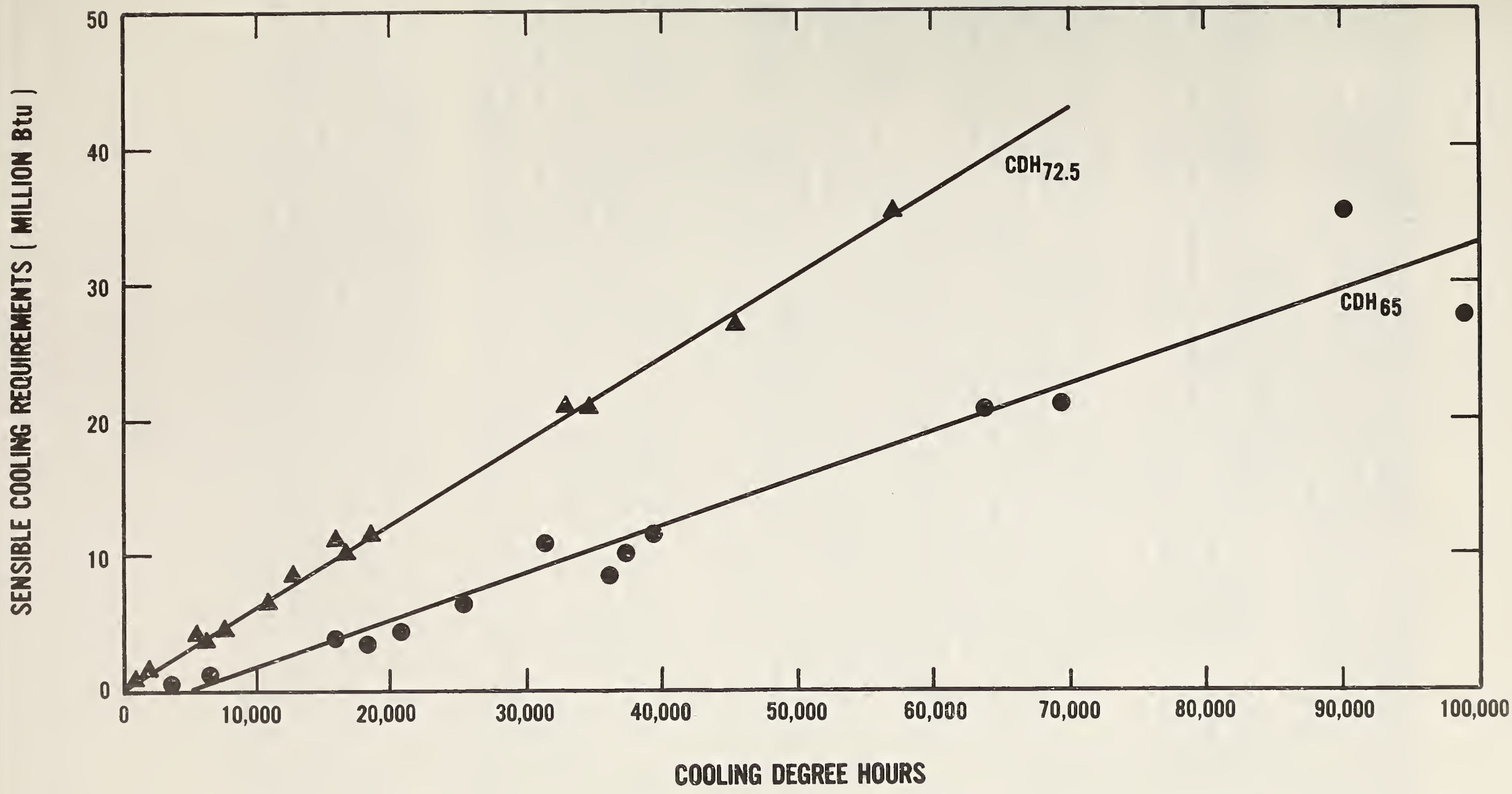

Figure 7.3 Annual sensible cooling requirements as a function of CHD_{65} and $CHD_{72.5}$ (H4 house)

the envelope is modified, the reduction in heating or cooling requirements may not correlate well with degree days or degree hours calculated at either the pre-modification or post-modification balance point. In addition, the change in the number of degree days or degree hours between different balance points is not proportional for each location.

Regression analyses were made for three major variations of the basic house (H0 to H4, H4 to H10, and H10 to H15), with the change in heating and sensible cooling requirements correlated with the number of heating degree days and cooling degree hours, respectively, over the range of calculation bases shown in tables 7.1 and 7.5. The best correlations are shown in tables 7.7 and 7.8 for heating and cooling, respectively.

It is important to note that in table 7.7 the best degree-day-base correlation for reductions in heating requirements is significantly higher than the best degree-day-base correlation for the heating requirements themselves. The best correlation was found to be 62.5°F for the first group of modifications (H0 to H4) and 60°F for the subsequent modifications. This implies that in developing recommendations for optimal levels of conservation in envelope design, the best heating degree day base is approximately 5°F to 7.5°F higher than that base most appropriate for estimating actual heating requirements.

Similarly, table 7.8 shows the cooling degree hour base which correlates most closely with reductions in sensible cooling requirements ($t_o \geq t_i$). This base temperature is significantly higher than the base temperature which correlated most closely with absolute cooling requirements shown in table 7.6. This implies that recommendations for energy conservation modifications aimed at reducing cooling requirements above the thermostat setpoint should be based on cooling degree hours calculated at approximately the thermostat setpoint (78°F).

Generalized data bases for estimating reductions in annual heating and cooling requirements, by climate zone, are shown in tables 7.9 and 7.10, respectively. In table 7.9, the reductions in annual heating requirements (ΔAHR) in Btu per square foot of component area for each of the 15 modifications, are shown as a function of HDD_{60}. (Heating degree days calculated at base 60°F are used rather than the traditional 65°F base because it provides a better basis for estimating ΔAHR. A map of HDD_{60} bands for the United States is shown in appendix C.) The reductions shown in table 7.9 are based on linear regression equations, using HDD_{60} in all cases, but are adjusted manually below 1000 HDD_{60} in order to provide better estimates in the low end.

In table 7.10, the reductions in annual cooling requirements (ΔACR), in Btu per square foot of component area for the same modifications, are shown as a function of $CDH_{77.5}$. ($CDH_{77.5}$ data for 41 locations in the United States have been calculated and are provided in table C-1 of appendix C.) The ΔACR data shown in table 7.10 were calculated based on regression equations estimated using $CDD_{77.5}$ in all cases. (Note that no cooling savings are estimated in regions with less than 2000 CDH since central air conditioning is seldom used in those regions.)

Table 7.7 Best Linear Regression Results: Heating Degree Days and Reductions in Annual Heating Requirements

Change	HDD Base	Regression Equation Constant	Slope	R^2	Standard Deviation of Residuals
H0 to H4	62.5F	0.729	7.20×10^{-3}	0.997	0.835
H4 to H11	60.0F	-0.103	2.50×10^{-3}	0.993	0.426
H11 to H15	60.0F	-0.141	1.22×10^{-3}	0.994	0.186

Table 7.8 Best Linear Regression Results: Cooling Degree Hours and Reductions in Annual Cooling Requirements

Change	CDH Base	Regression Equation Constant	Slope	R^2	Standard Deviation of Residuals
H0 to H4	77.5F	0.438	3.56×10^{-4}	0.959	0.755
H4 to H10	77.5F	0.077	1.04×10^{-4}	0.991	0.101
H11 to H15	77.5F	0.219	0.74×10^{-4}	0.960	0.154

Table 7.9 Incremental Reduction in AHR (1000 Btu/Ft^2) by Modification and HDD_{60}

Option	Heating Degree Days (Base 60°F) 500	1000	2000	3000	4000	5000	6000	7000	8000	9000
Attic Insulation										
R-11	2.90	4.795	7.630	10.464	13.299	16.134	18.968	21.803	24.638	27.472
R-19	0.39	0.693	1.184	1.676	2.167	2.659	3.150	3.642	4.133	4.625
R-30	0.18	0.359	0.708	1.058	1.408	1.757	2.107	2.456	2.806	3.156
R-38	0.07	0.134	0.275	0.416	0.556	0.697	0.838	0.979	1.120	1.261
R-49	0.05	0.103	0.225	0.348	0.471	0.594	0.716	0.839	0.962	1.085
Wall Insulation										
R-11	1.65	2.999	5.239	7.479	9.718	11.958	14.198	16.438	18.678	20.918
R-13	0.07	0.141	0.295	0.450	0.604	0.759	0.913	1.068	1.222	1.376
R-19	0.20	0.403	0.817	1.231	1.645	2.058	2.472	2.886	3.300	3.713
R-23	0.09	0.197	0.452	0.707	0.962	1.217	1.472	1.727	1.982	2.237
Floor Insulation										
R-11	0.38	0.754	2.032	3.310	4.588	5.866	7.144	8.423	9.701	10.979
R-19	0.08	0.144	0.419	0.694	0.969	1.244	1.519	1.794	2.069	2.344
Windows and Doors										
DBLGLZ	6.30	12.184	23.964	35.744	47.525	59.305	71.086	82.866	94.646	106.427
TPLGLZ	1.75	3.356	7.394	11.432	15.470	19.508	23.546	27.584	31.622	35.660
DBLSGD	5.10	10.404	21.252	32.100	42.948	53.796	64.644	75.492	86.340	97.189
STMDR	1.75	3.151	7.048	10.945	14.841	18.738	22.635	26.531	30.428	34.325

Table 7.10 Incremental Reduction in ACR (1000 Btu/Ft^2) by Modification and $CDH_{77.5}$

	Cooling Degree Hours (Base 77.5°F)								
Option	2500	5000	7500	10,000	15,000	20,000	25,000	30,000	40,000
Attic Insulation									
R-11	0.854	1.484	1.967	2.375	3.058	3.635	4.143	4.602	5.417
R-19	0.180	0.359	0.497	0.613	0.807	0.971	1.115	1.246	1.478
R-30	0.130	0.224	0.296	0.357	0.460	0.546	0.622	0.690	0.812
R-38	0.053	0.092	0.122	0.147	0.189	0.225	0.256	0.285	0.335
R-49	0.043	0.082	0.113	0.138	0.181	0.218	0.249	0.278	0.330
Wall Insulation									
R-11	0.592	1.012	1.433	1.853	2.694	3.534	4.375	5.216	6.897
R-13	0.041	0.075	0.101	0.123	0.160	0.192	0.219	0.244	0.288
R-19	0.135	0.248	0.334	0.407	0.529	0.632	0.722	0.804	0.950
R-23	0.040	0.088	0.126	0.157	0.210	0.255	0.294	0.330	0.393
Floor Insulation									
R-11	-0.538	-0.698	-0.792	-0.859	-0.952	-1.019	-1.071	-1.113	-1.179
R-19	-0.100	-0.100	-0.100	-0.100	-0.100	-0.100	-0.100	-0.100	-0.100
Windows and Doors									
DBLGLZ	0.833	2.001	3.169	4.337	6.674	9.010	11.346	13.682	18.355
TPLGLZ	0.848	1.634	2.420	3.205	4.777	6.348	7.919	9.491	12.633
DBLSGD	1.430	2.821	4.213	5.604	8.387	11.170	13.952	16.735	22.301
STMDR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The data in tables 7.9 and 7.10 will serve as the principal focus of the life-cycle cost analysis in the following section. They have been adjusted to a square foot basis in order to make them more useful in developing general guidelines for insulating single-family housing. In addition, they have been grouped by component in order to facilitate subsequent analysis. However, it should be kept in mind that the data were developed in a sequential ordering according to a generally decreasing savings-to-cost relationship.

8. LIFE-CYCLE COST ANALYSIS OF SELECTED ENVELOPE MODIFICATIONS

Section 3 outlined an economic framework for determining the optimal thermal envelope configuration for residential buildings. In particular, that section stressed the need to calculate marginal, or incremental, dollar savings and costs of additional modifications to the building envelope in present value, life-cycle terms in order to determine an optimal envelope design. In sections 6 and 7, incremental reductions in annual heating and cooling requirements were calculated for 15 envelope component modifications. In this section, the incremental present-value, life-cycle dollar savings and corresponding costs are computed for each of these modifications in order to determine the extent to which those modifications should therefore be incorporated into the building envelope design. The solution, of course, is dependent on a number of factors, including climate, energy prices, heating and cooling system conversion efficiencies, the costs of the modifications, the useful lifetime expectancy for the building envelope, and the discount rate used to convert future costs or savings to present value.

8.1 CALCULATION OF PRESENT-VALUE, LIFE-CYCLE SAVINGS

The reductions in annual heating and cooling requirements calculated in sections 6 and 7 can be converted into incremental present-value, life-cycle dollar savings as follows:

$$\Delta S_i = \frac{\Delta AHR_i}{\eta_h} (P_h \ UPW_h^*) + \frac{\Delta ACR_i}{\eta_c} (P_c \ UPW_c^*) \qquad (8\text{-}1)$$

where:

ΔS_i = the incremental present-value, life-cycle dollar savings attributable to the i^{th} envelope design modification,

ΔAHR_i = the reduction in annual heating requirements attributable to the i^{th} modification,

ΔACR_i = the reduction in annual cooling requirements attributable to the i^{th} modification,[1]

η = seasonal equipment efficiency or seasonal coefficient of performance (COP),[2]

P = energy price (in the same units as ΔAHR and ΔACR),

UPW^* = modified uniform present worth factor (to relate future dollar savings to present value), and subscripts,

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[1] An increase in annual cooling requirements is expressed in terms of a negative reduction.

[2] For a heat pump COP = SEER/3.143 Btuh/W, where SEER = seasonal energy efficiency ratio (Btuh/W).

h = heating, and
c = cooling.

Equation (8-1) can be reduced to

$$\Delta S_i = F_1 \ (\Delta AHR_i) + F_2 \ (\Delta ACR_i) \tag{8-2}$$

where $F_1 = \dfrac{P_h \ UPW_h^*}{\eta_h}$, and (8-3)

$$F_2 = \frac{P_c \ UPW_c^*}{\eta_c}. \tag{8-4}$$

This is convenient for calculation purposes because F_1 and F_2 are assumed to remain constant as the overall envelope is thermally upgraded. (This implicitly assumes that all modifications considered have the same useful life as that of the building envelope; this may require some adjustment to the cost of some modifications in order to prolong their lives; e.g. storm doors.) F_1 and F_2 will sometimes be referred to as heating and cooling index numbers, respectively, in the remainder of this report.

Table A-3 in appendix A provides UPW* factors for a range of discount rates, energy price escalation rates, and lifetime assumptions that are frequently used in the life-cycle cost analysis of buildings. Table A-4 provides the cost per million Btu output to the conditioned space by the heating equipment for gas, oil, and electricity as a function of unit prices and heating system efficiencies.[1] Table A-5 provides the cost per million Btu output by the air conditioning system as a function of electricity prices and the seasonal coefficient of performance (SCOP).[2]

F_1 and F_2 can be calculated by multiplying the appropriate UPW* factor and the cost per million Btu output for heating or cooling, respectively. For example, A-3 shows that for an envelope life of 30 years, an annual rate of energy price increase (real) of 4 percent, and a (real) discount rate of 4 percent, the UPW* is 30. Table A-4 shows that at $0.40 per therm and 70 percent seasonal efficiency, the cost per million Btu output to the conditioned space is $5.71. F_1 is therefore equal to (30 x $5.71/million Btu) $171.30 per million Btu. This is, in essence, the present value of one million Btu of heating energy saved each year over 30 years. Assuming that electricity costs are currently $0.048 per kWh and are expected to increase annually at a real rate of 2 percent, and that the seasonal COP for the air conditioner is 2.35, the UPW* from table A-3 equals 22.5 and the cost per million Btu delivered from table A-5 equals $5.96. Thus, F_2 equals (22.5 x $5.96/million Btu) $134.10 per million Btu. In a geographic region having 4000 HDD_{60} and 7500 $CDH_{77.5}$, the

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1 The heating system efficiency should be estimated in terms of seasonal performance and should include distribution losses (e.g., from ductwork).

2 SCOP = Seasonal Energy Efficiency Ratio (in Btuh/W)/3.413 Btuh/W.

the ΔAHR for R-11 attic insulation (relative to R-0) is 0.0133 million Btu per square foot and the ΔACR for R-11 attic insulation is 0.002 million Btu per square foot. Thus the present-value, life-cycle savings are equal to $2.55 ($171.3/million Btu x 0.0133 million Btu + $134.10/million Btu x 0.002 million Btu) per square foot of attic area.

A general format for calculating incremental savings for the i^{th} modification (ΔS_i) is shown in table 8.1. Once the F_1 and F_2 values are known for a given house in a given location, the incremental savings can be easily calculated based on this procedure. These incremental savings are potentially useful to the builder/buyer because they can be used to determine the maximum cost for any modification that can be economically justified on a life-cycle cost basis. Localized tables of incremental savings could be produced for builders and buyers to use in the design process, sensitive to local climate factors, energy costs, and equipment efficiencies.

8.2 CALCULATION OF PRESENT-VALUE, LIFE-CYCLE COSTS

In order to determine an optimal combination of envelope design modifications to reduce design energy requirements, incremental dollar savings must be compared with corresponding incremental modification costs. The major component of that incremental cost is the additional purchase cost of a new home.[1] In fact, economic analyses of energy conservation modifications seldom go beyond this initial cost. However, the other cost components discussed briefly in section 3 may be of some importance, depending upon the assumptions of the user. For example, replacement costs at specified intervals may be considered necessary for some modifications (e.g., storm doors) in order to bring them up to the same life expectancy used for the envelope in the analysis of incremental life-cycle savings. Increased maintenance and repair costs for the modifications considered in this report are not expected to be significant. However, for other modifications (e.g., weatherstripping) these costs may be significant and thus these costs should be considered in a general methodology. Replacement, maintenance and repair costs should all be converted to present-value terms using the appropriate equations from table 3.1.

If the increased cost of a house due to energy conservation modifications is to be financed as part of the mortgage, adjustments can be made to determine the present value of the mortgage payments and the present value of the income tax savings due to interest payments. Table A-1 in appendix A provides the present value of the mortgage payments for a range of discount rates, interest rates, and repayment period, based on equal monthly payments throughout the loan life. Table A-2 in appendix A provides the corresponding present-value of interest payments made, discounted from the end of the year. Thus the tax savings can be calculated as the product of the owner's income tax bracket and the present-value of interest payments. For example, with a 12 percent (nominal) discount rate and a 30-year mortgage at 10 percent (nominal) interest

[1] This increased purchase cost should include not only the nominal purchase price but any increase in closing costs as well.

Table 8.1 Calculation Procedures for Incremental Savings

(Savings per square foot of surface area)

A. Calculate F_1 (heating)

(1) Price per million Btu output (from table A-4) $\underset{(1)}{\underline{\hspace{3cm}}}$

(2) Modified Uniform Present Worth Factor (from table A-3) $\underset{(2)}{\underline{\hspace{2cm}}}$

(3) $F_1 = \underset{(1)}{\underline{\hspace{3cm}}} \times \underset{(2)}{\underline{\hspace{3cm}}} = \underset{(3)}{\underline{\hspace{3cm}}}$

B. Calculate F_2 (cooling)

(4) Price per million Btu output (from table A-5) $\underset{(4)}{\underline{\hspace{3cm}}}$

(5) Modified Uniform Present Worth Factor (from table A-3) $\underset{(5)}{\underline{\hspace{2cm}}}$

(6) $F_2 = \underset{(4)}{\underline{\hspace{3cm}}} \times \underset{(5)}{\underline{\hspace{3cm}}} = \underset{(6)}{\underline{\hspace{3cm}}}$

C. Calculate ΔS_i

(7) ΔAHR_i (from table 7.9) $\underset{(7)}{\underline{\hspace{3cm}}}$

(8) ΔACR_i (from table 7.10) $\underset{(8)}{\underline{\hspace{3cm}}}$

(9) $\Delta S_i = \underset{(3)}{\underline{\hspace{2cm}}} \times \underset{(7)}{\underline{\hspace{2cm}}} + \underset{(6)}{\underline{\hspace{2cm}}} \times \underset{(8)}{\underline{\hspace{2cm}}} = \underset{(9)}{\underline{\hspace{1.5cm}}}$

rate,[1] the present value of the mortgage payments for an additional $1000 borrowed is $894 (from table A-1). The corresponding present value of the interest payments is $725 (from table A-2). In a 25 percent tax bracket, this equates to a present-value tax savings of $181 (0.25x$725). Thus, the effective present-value cost of borrowing $1000 is $713 ($894-181) in this example. (Table A-1 shows how to find the real discount rate equivalent to the nominal discount rates used. For a general inflation rate of 10 percent, a nominal discount rate of 12 percent is approximately equivalent to a real discount rate of 2 percent.)

In addition, the present value of increased property taxes and insurance costs should be added to the cost of each modification. These costs should be calculated over the same lifetime used in calculating the life-cycle energy savings. Appendix B describes a methodology for calculating these costs. Table B-1 in appendix B provides factors which can be multiplied by the increased purchase cost of a house due to energy conservation modifications in order to estimate the present value of both property tax and insurance costs. These factors are based on the owner's discount rate, annual property tax and insurance rates (per dollar of actual building value), and the projected annual rate of energy price increase over the building life used in the life-cycle cost analysis. For example, for a building life of 30 years, a (real) discount rate of 2 percent, a (real) rate of energy price increase of 2 percent, and net property tax rate[2] plus insurance rate of 2 percent, the present value factor is 0.33. Thus for an energy conservation modification which adds $1000 to the price of a house, the present value of the additional property taxes and insurance costs is estimated to be $330 (0.33 x $1000). It should be noted that, while this factor is consistent with life-cycle cost assumptions, it may overstate the actual change in assessment for tax and insurance purposes computed by the assessor.

It is difficult to make general conclusions about the effects of mortgage payment adjustments and property tax and insurance cost adjustments to the increase in initial purchase cost because of the wide variation in the variables needed to calculate these effects. In the examples shown above, where the present-value cost of repaying $1000 over 30 years is $713 and the additional present-value property taxes and insurance cost per $1000 additional house cost is $330, the net effect of these two adjustments is insignificant since they nearly cancel out. The use of a real discount rate greater than 2 percent will result in a net present-value conservation cost less than the $1000 initial cost, while the use of a lower discount rate will result in a higher present-value cost than $1000, where the other variables are held the

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1 An annual inflation rate of 10 percent is assumed in reconciling the nominal nature of the mortgage interest rate with the real nature of the discount rate.

2 The net property tax rate is the rate adjusted for income tax savings. Thus in a 20 percent tax bracket, a 2.5 percent property tax rate is equivalent to a 2 percent (2.5 x (1-0.2) net rate. Effective residential tax rates for selected cities are shown in table B-2 in appendix B.

same. However, a higher tax bracket will reduce the net present-value cost; a higher interest rate will increase the net present-value cost; a higher property tax rate will increase the net present-value cost. In many cases these adjustments may add complexities to the economic analysis that are not justified from the average homeowner's standpoint because of the uncertainties involved.

A general format for calculating incremental costs for the i^{th} energy conservation modification is shown in table 8.2. When the total incremental present-value cost for the i^{th} modification has been calculated, it can be compared with the incremental present-value savings (calculated in table 8.1) for the corresponding modification. All incremental modifications with incremental savings greater than or equal to incremental costs are included in the optimal envelope configuration.

8.3 CALCULATION OF OPTIMAL ENVELOPE COMPONENT MODIFICATIONS

Given the incremental savings and costs for the modifications considered, the optimal level of modification to any building envelope component analyzed can be found by incorporating all modifications with incremental savings greater than or equal to incremental costs into the component specifications. Table 8.3 shows an example of this decision process for the six components analyzed in sections 6 and 7. This example is based on a location with 4000 HDD_{60} and 7500 $CDH_{77.5}$. The cost data is from table 4.6, unadjusted for replacement, maintenance, repair, or present value of mortgage payments, interest tax savings, property tax and insurance costs. A heating index (F_1) of 200 is used, corresponding to natural gas heating at $0.46 per therm, 70 percent seasonal furnace efficiency, and a modified uniform present worth factor (UPW*) of 30. (See table 8.4 for other equivalent assumptions that result in an F_1 of 200. Table A-3 in appendix A provides the assumptions that equate to a UPW* of 30.) A cooling index (F_2) of 200 is used, corresponding to central electric air conditioning with a seasonal COP of 2.35 (SEER = 8.0), a price per kWh of $0.053, and a UPW* of 30. (See table 8.5 for other equivalent assumptions that result in an F_2 of 200.) The modifications with asterisks in table 8.3 represent the optimal level of thermal improvement for each component of the building envelope. No further improvement will produce incremental savings large enough to amortize the additional costs incurred.

Based on these same costs, the optimal level of thermal improvement for each of these same components has been calculated for a wide range of climates and heating and cooling index numbers (F_1 and F_2, respectively). Table 8.6 shows the optimal levels calculated for heating only (i.e., air conditioning is not used) in six heating degree day (base 60°F) regions and for five values of F_1, ranging from 100 to 500. Several alternative assumptions which equate to each F_1 value used are shown in table 8.4. Table 8.7 shows the optimal levels calculated for both heating and cooling savings in six combined HDD_{60} and $CDH_{77.5}$ regions. (While these combined regions are representative of the general relationship between HDD_{60} and $CDH_{77.5}$, there is significant variation between these two variables, so that they do not include all regions of the United States.) Five combinations of F_1 and F_2 values are shown. However, there is no fixed relationship between F_1 and F_2; these are meant to be representative only. Several alternative assumptions which equate to each F_2 value used are shown in table 8.5.

Table 8.2 Calculation Procedures for Incremental Costs

A. Calculation of Net Present-Value Purchase Costs

(1) Additional Purchase Cost Due to i^{th} Modification ____________ (1)

(2) Percent Down Payment ____________ (2)

(3) Amount Financed = ____________ (1) x (1- ____________ (2)) = ____________ (3)

(4) Present Value of Mortgage Payments per $1000 Borrowed (from table A-1) ____________ (4)

(5) Present Value of Mortgage Payments

____________ (3) x ____________ (4) / 1000 = ____________ (5)

(6) Present Value of Interest Payments per $1000 Borrowed (from table A-2) ____________ (6)

(7) Income Tax Bracket ____________ (7)

(8) Present Value of Tax Savings From Interest

____________ (5) x ____________ (6) x ____________ (7) / 1000 = ____________ (8)

(9) Net Present Value of Purchase Cost for i^{th} Modification

[____________ (1) x ____________ (2)] + ____________ (6) - ____________ (8) = ____________ (9)

B. Calculation of Replacement, Maintenance and Repair Costs

(10) Present Value of Replacement Costs (use equation (3-1) to discount future costs to present value) ____________ (10)

(11) Annually Recurring Maintenance and Repair Costs (first year) ____________ (11)

Table 8.2 (Continued)

(12) Uniform Present Worth Factor for (11) (use equation (3-2) to find factor)

__________ (12)

(13) Present-Value, Life-Cycle Maintenance and Repair Costs (annually recurring)

__________ (11) x __________ (12) = __________ (13)

(14) Present Value of Non-Annually Recurring Maintenance and Repair Costs (use equation (3-1) to discount future costs to present value)

__________ (14)

(15) Total Present Value, Life-Cycle Replacement, Maintenance, and Repair Costs for i^{th} Modification

__________ (15)

C. Estimate of Property Tax and Insurance Costs

(16) Property Tax and Insurance Cost Factor

__________ (16)

(17) Present Value, Life-Cycle Property Taxes and Insurance Costs for i^{th} Modification

__________ (1) x __________ (16) = __________ (17)

D. Total Incremental Cost for i^{th} Modification (ΔC_i)

(18) __________ (9) + __________ (15) + __________ (17) = __________ (18)

Table 8.3 Example Solution of Optimal Component Modifications

Heating Degree Days (Base 60°F) = 4000
Cooling Degree Hours (Base 77.5°F) = 7500
F_1 = 200 F_2 = 200

(1) Component	(2) ΔAHR (10^3 Btu/ft^2)	(3) ΔAHR/1000 x F_1	(4) ΔACR (10^3 Btu/ft^2)	(5) ΔACR/1000 x F_2	(6) ΔSavings ($/ft^2) (3) + (5)	(7) ΔCost ($/ft^2)
1. Attic Insulation						
R-11	13.299	$2.66	1.967	0.39	3.05	$0.20
R-19	2.167	0.43	0.497	0.10	0.53	0.09
R-30	1.408	0.28	0.296	0.06	0.34	0.14
R-38*	0.556	0.11	0.122	0.02	0.14	0.09
R-49	0.471	0.09	0.113	0.02	0.12	0.14
2. Wall Insulation						
R-11	9.718	1.94	1.433	0.29	2.23	0.23
R-13	0.604	0.12	0.101	0.02	0.14	0.07
R-19*	1.645	0.33	0.334	0.07	0.40	0.30
R-23	0.962	0.19	0.126	0.03	0.22	0.30
3. Floor Insulation						
R-11	4.588	0.92	-0.792	-0.16	0.76	0.23
R-19*	0.969	0.19	-0.100	-0.02	0.17	0.11
4. Window Glazing						
Double	47.525	9.51	3.169	0.63	10.14	2.58
Triple*	15.470	3.09	2.420	0.48	3.58	2.93
5. Double-Glazed Sliding Glass Door*	42.948	8.59	4.213	0.84	9.43	4.50
6. Storm Door	14.841	2.97	0.0	0.0	2.97	7.50

* Indicates that optimal envelope configuration includes this modification.

Table 8.4 Representative Assumptions for Selected Values of F_1 (Heating)

F_1	Heating Energy	Energy Price/Unit	Seasonal Efficiency	UPW*
100	Gas	$0.23/therm	0.70	30
	Electric	0.011/kWh	1.00	30
	Electric	0.017/kWh	1.50[a]	30
	Electric	0.023/kWh	2.00[a]	30
200	Gas	$0.46/therm	0.70	30
	Oil	0.65/gallon	0.70	30
	Electric	0.023/kWh	1.00	30
	Electric	0.035/kWh	1.50[a]	30
	Electric	0.046/kWh	2.00[a]	30
300	Gas	$0.69/therm	0.70	30
	Oil	0.98/gallon	0.70	30
	Electric	0.034/kWh	1.00	30
	Electric	0.051/kWh	1.50[a]	30
	Electric	0.068/kWh	2.00[a]	30
400	Gas	$0.92/therm	0.70	30
	Oil	$1.31/gallon	0.70	30
	Electric	0.045/kWh	1.00	30
	Electric	0.068/kWh	1.50[a]	30
	Electric	0.090/kWh	2.00[a]	30
500	Oil	$1.64/gallon	0.70	30
	Electric	$0.057/kWh	1.00	30
	Electric	0.086/kWh	1.50[a]	30
	Electric	0.114/kWh	2.00[a]	30

[a] Heat Pump Heating Seasonal Performance Factor (HSPF)

Table 8.5 Representative Assumptions for Selected Values of F_2 (Cooling)

F_2	Price/kWh (for cooling)	Seasonal Efficiency COP[a]	Seasonal Efficiency SEER[b]	UPW*
100	\$0.020	1.75	6	30
	\$0.027	2.35	8	30
	\$0.033	2.90	10	30
200	\$0.040	1.75	6	30
	\$0.053	2.35	8	30
	\$0.067	2.90	10	30
300	\$0.060	1.75	6	30
	\$0.080	2.35	8	30
	\$0.100	2.90	10	30

[a] COP = Coefficient of Performance

[b] SEER = Seasonal Energy Efficiency Ratio

Table 8.6 Optimal Component Specifications for Selected Values of F_1 (Heating Only)[a]

F_1	Component	Heating Degree Days (Base 60°F)[b]					
		1,000	2,000	3,000	4,000	6,000	8,000
	Attic	R-11	R-19	R-19	R-30	R-30	R-38
	Wall	R-11	R-11	R-11	R-11	R-13	R-19
100	Floor	R-0	R-0	R-11	R-11	R-19	R-19
	Windows	Single	Single	Double	Double	Double	Triple
	Sliding Glass Door	Single	Single	Single	Single	Double	Double
	Storm Door	no	no	no	no	no	no
	Attic	R-19	R-30	R-30	R-38	R-49	R-49
	Wall	R-11	R-11	R-13	R-19	R-19	R-23
200	Floor	R-0	R-11	R-19	R-19	R-19	R-19
	Windows	Single	Double	Double	Triple	Triple	Triple
	Sliding Glass Door	Single	Single	Double	Double	Double	Double
	Storm Door	no	no	no	no	no	no
	Attic	R-19	R-30	R-38	R-49	R-49	R-49
	Wall	R-11	R-13	R-19	R-19	R-23	R-23
300	Floor	R-11	R-19	R-19	R-19	R-19	R-19
	Windows	Double	Double	Triple	Triple	Triple	Triple
	Sliding Glass Door	Single	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	no	yes
	Attic	R-30	R-38	R-49	R-49	R-49	R-49
	Wall	R-11	R-19	R-19	R-23	R-23	R-23
400	Floor	R-11	R-19	R-19	R-19	R-19	R-19
	Windows	Double	Triple	Triple	Triple	Triple	Triple
	Sliding Glass Door	Single	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	yes	yes
	Attic	R-30	R-38	R-49	R-49	R-49	R-49
	Wall	R-13	R-19	R-23	R-23	R-23	R-23
500	Floor	R-11	R-19	R-19	R-19	R-19	R-19
	Windows	Double	Triple	Triple	Triple	Triple	Triple
	Sliding Glass Door	Double	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	yes	yes

[a] Based on incremental modification cost shown in table 4.6 and reductions in AHR shown in table 7.9.

[b] See HDD_{60} map in appendix C.

Table 8.7 Optimal Component Specifications for Selected Values of F_1 and F_2 (Heating and Cooling)[a]

F_1/F_2	Component	Heating Degree Days (Base 60°F)[b] 1,000	2,000	3,000	4,000	6,000	8,000
		Cooling Degree Hours (Base 77.5°F)[c] 20,000	15,000	10,000	7,500	5,000	2,500
100/200	Attic	R-30	R-30	R-30	R-30	R-38	R-38
	Wall	R-11	R-11	R-13	R-13	R-19	R-19
	Floor	R-0	R-0	R-0	R-11	R-19	R-19
	Windows	Double	Double	Double	Double	Double	Triple
	Sliding Glass Door	Single	Single	Single	Double	Double	Double
	Storm Door	no	no	no	no	no	no
200/200	Attic	R-30	R-38	R-38	R-38	R-49	R-49
	Wall	R-13	R-13	R-19	R-19	R-23	R-23
	Floor	R-0	R-0	R-19	R-19	R-19	R-19
	Windows	Double	Double	Triple	Triple	Triple	Triple
	Sliding Glass Door	Single	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	no	no
300/200	Attic	R-38	R-38	R-38	R-49	R-49	R-49
	Wall	R-13	R-19	R-19	R-23	R-23	R-23
	Floor	R-0	R-19	R-19	R-19	R-19	R-19
	Windows	Double	Triple	Triple	Triple	Triple	Triple
	Sliding Glass Door	Double	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	no	yes
400/200	Attic	R-38	R-38	R-49	R-49	R-49	R-49
	Wall	R-13	R-19	R-23	R-23	R-23	R-23
	Floor	R-0	R-19	R-19	R-19	R-19	R-19
	Windows	Double	Triple	Triple	Triple	Triple	Triple
	Sliding Glass Door	Double	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	yes	yes
500/300	Attic	R-38	R-49	R-49	R-49	R-49	R-49
	Wall	R-19	R-19	R-23	R-23	R-23	R-23
	Floor	R-0	R-19	R-19	R-19	R-19	R-19
	Windows	Triple	Triple	Triple	Triple	Triple	Triple
	Sliding Glass Door	Double	Double	Double	Double	Double	Double
	Storm Door	no	no	no	no	yes	yes

[a] Based on incremental modification costs shown in table 4.5, reductions in AHR shown in table 7.9, and reductions in ACR shown in table 7.10.

[b] See HDD_{60} map in appendix C.

[c] See $CDH_{77.5}$ for selected cities in table C-1 of appendix C.

Tables 8.6 and 8.7 provide an interesting data base for making some general observations about the optimal level of conservation modifications to building envelope components for single-family housing.

(1) A minimum of R-30 attic insulation appears to be cost-justified in all houses having central air conditioning. Even without central air conditioning, R-30 attic insulation is justified in all but the mildest heating climates at current (1980) energy prices. R-49 attic insulation, the highest level examined in this report, becomes cost effective in more than half of the United States when oil or electric resistance heating is used at typical 1980 energy prices.

(2) A minimum of R-11 wall insulation appears to be cost effective for wood-frame walls in all regions of the country. In more than half the country R-19 and R-23 levels are optimal on a life-cycle basis unless heating fuel costs are very low (e.g. less than $0.25 per therm for gas).

(3) Floor insulation over unheated crawlspaces is not cost effective in regions dominated by air conditioning requirements unless heating costs are very high relative cooling costs. However, in most of the United States, R-19 floor insulation over unheated crawlspaces can be economically justified unless heating costs are very low.

(4) Double glazing appears to be cost effective in all but the mildest climates with low heating energy costs. Triple glazing becomes cost effective in most of the United States, with even moderate energy costs.

(5) Double glazing on sliding glass doors in cost effective in most regions of the United States except when heating energy costs are very low.

(6) Storm doors are not likely to be cost effective outside of the coldest regions of the United States unless fuel prices are very high. However, if most of the cost of the storm door can be attributed to additional security and to its screen door function during the summer months, this option is likely to be cost justified in other regions as well.

9. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER RESEARCH

9.1 SUMMARY

The purpose of this report was to investigate, in a systematic manner, the extent to which energy conservation modifications to the envelope design of single-family housing can be cost justified. A life-cycle, benefit-cost model was outlined and economic decision-making criteria were formulated to determine the minimum-life-cycle-cost envelope design. The interdependent relationships between and within building components were examined. A priority ranking methodology was described and used to calculate reductions in heating and cooling requirements due to component modifications in 14 geographic locations. These reductions were then correlated with corresponding heating degree days and cooling degree hours in order to provide a basis for estimating energy savings in any location in the United States. A method for calculating optimal component configurations was outlined and optimal configurations were developed for a wide range of climate data and energy prices.

This report represents a significant advance over previous work of a similar nature because the heating and cooling requirements and reductions in those requirements were estimated using a dynamic load determination program, NBSLD, instead of steady-state methods and aggregate climatic data. Actual hourly climatic data for each location examined were utilized. In addition, the thermal interdependence among the envelope components was considered to a greater degree than in previous reports. Results of the thermal analysis were reported in considerable detail, including annual heating and cooling requirements, design heating and cooling loads, annual heating and cooling hours corresponding to changes in the envelope design, and heat gain and loss through south-facing windows and walls of the four major orientations during heating and cooling hours.

In addition, a methodology for adjusting present-value modification cost data for mortgage payments, property taxes and insurance costs over the time horizon was presented.

9.2 CONCLUSIONS

A number of significant conclusions can be derived from this report.

(1) Optimal envelope design configurations vary over a wide range depending on climate, energy costs, and modification costs. For example, optimal attic insulation resistances in houses with electric heat and central air conditioning range from R-30 in Miami to R-49 or more in Minneapolis. If only heating reductions are considered, optimal attic insulation levels may be less than R-11 in the mildest winter regions of the United States (e.g., southern Florida).

(2) Increasing the size of south-facing, double-glazed windows in a well-insulated house, without corresponding decreases in window area on the other walls, will reduce heating loads in very few locations unless substantial internal mass is available and/or window management

techniques such as thermal shutters are used to reduce heat losses during periods when the sun is not shining. A night setback of the thermostat during heating periods will increase the relative benefits of large south-facing windows compared to a uniform day-night thermostat setting.

(3) The compass orientation of a house appears to have little effect on its heating requirements except for the orientation of its windows. Instead the total opaque wall surface area is more important. However, the orientation of the house significantly affects cooling requirements: north- and south-facing together walls are considerably more energy efficient than those facing east and west. Orientation of windows and daily living areas away from the north side and toward the south side of the house appears to have more effect on reducing annual heating requirements than the actual orientation of the house. Because the north-facing wall loses significantly more heat than the south-facing wall, consideration should be given to improving its thermal characteristics relative to those of the other walls in locations where heating loads predominate.

(4) Modified heating degree day and cooling degree hour data can provide a useful and relatively accurate means of interpolating heating and cooling (sensible) requirements to other locations based on more precise calculations in known climates. In addition, this modified data can be used to correct the results based on Test Reference Year (TRY) climatic data, in order to better reflect long-term climatic trends.

(5) Reductions in annual heating requirements are generally more than proportional to reductions in design loads. Thus, methodologies which base reductions in heating requirements on reductions in design loads will underestimate the potential savings from envelope design modifications. The opposite is true for reductions in annual cooling requirements, where they tend to be significantly less than proportional to design loads. This lack of direct proportionality may have significant implications with respect to equipment sizing and part-load operations.

9.3 RECOMMENDATIONS FOR FURTHER RESEARCH

This report provides a new insight into the economic and thermal aspects of energy conservation in new housing design. However, a number of important issues require further research. These can be divided into two categories: (A) technical issues, and (B) economic issues.

(A) Technical issues relate to the ability to better quantify the effects of design changes on annual energy requirements. These include:

(1) Refinements to NBSLD (and similar load-estimating programs) to improve algorithms and data bases related to

(a) attic temperatures,

(b) the effects of heat absorption on heat transfer through architectural glass,

(c) the thermal coupling of zones within a building,

(d) the modeling of internal mass without distorting envelope component specifications,

(e) radiation exchange modeling,

(f) the simulation of window management techniques, (i.e., changes in shading and conduction on an hourly, daily, and seasonal basis),

(g) ground temperature data and heat transfer calculation through floors and walls below grade, and

(h) daylighting and its impact on lighting energy use in buildings.

(2) Estimates of actual energy requirements based on the part-load efficiencies of heating and cooling equipment,

(3) Improved analysis of passive solar measures,

(4) Improved data on the effects of envelope modifications to reduce air infiltration, and

(5) The effects of insulation and mass in reducing heating and cooling requirements in masonry wall buildings.[1]

(B) Economic issues are related to the determination of optimal building designs with respect to space heating and cooling. These include:

(1) More empirical analysis into life-cycle cost-related decision criteria for new home purchasers,

(2) The simultaneous determination of optimal envelope and equipment efficiencies,

(3) Improved modification cost data estimated on a regional basis,

(4) Improvements in the priority ranking process when better information on componnent interdependence can be produced.

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[1] The effects of mass and insulation in walls are examined in S. Petersen, K. Barnes, and B. Peavy, Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single-Family Housing, BSS-134, National Bureau of Standards, Washington, D.C., August 1981.

(5) Further analysis to demonstrate the viability of economic analysis in the establishment of "energy budget" data that can serve as economically justified, performance-oriented guidelines for new single-family housing design, and

(6) Improved projections of future energy costs that will enable the user to better project the dollar value of annual energy savings over the life of the building.

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APPENDIX A

SELECTED FACTORS FOR LIFE-CYCLE COST ANALYSIS

Table A-1. Present Value of Mortgage Payments per $1000 Borrowed[a]

(Monthly payments discounted from time of payment)

Annual Discount Rate (Nominal)[b]	Mortgage Life (years)	Annual Interest Rate (Nominal) 9%	10%	11%	12%	13%	14%	15%	16%	17%	18%
	20	961	1030	1102	1176	1251	1328	1406	1485	1566	1648
10%[b]	25	955	1034	1116	1199	1284	1370	1458	1547	1637	1727
	30	951	1037	1126	1216	1308	1401	1495	1590	1685	1782
	20	850	912	975	1040	1107	1175	1244	1314	1386	1458
12%	25	832	901	972	1045	1119	1194	1270	1348	1426	1505
	30	820	894	970	1048	1127	1207	1288	1370	1452	1535
	20	760	815	872	930	989	1050	1112	1175	1239	1303
14%	25	735	796	859	923	988	1055	1123	1191	1260	1330
	30	718	784	850	919	988	1058	1129	1201	1273	1346
	20	686	736	787	839	893	948	1004	1060	1118	1176
16%	25	658	712	768	826	884	944	1004	1065	1127	1189
	30	639	697	756	817	879	941	1004	1068	1132	1197
	20	572	614	657	700	745	791	838	885	933	982
20%	25	542	587	633	681	729	778	828	878	929	981
	30	523	571	619	669	720	771	822	875	927	980

[a] Calculation Procedure: $$\text{P.V. Mortgage Payments} = L \; \frac{i/12(1 + i/12)^{12n}}{(1 + i/12)^{12n} - 1} \; \frac{(1 + d_m)^{12n} - 1}{d_m(1 + d_m)^{12n}}$$

where L = initial loan amount,
i = annual interest rate,
d_m = monthly discount rate = $(1 + d)^{1/12} - 1$, and
d = annual discount rate, and
n = loan life in years.

Mortgage payments are calculated and discounted on a monthly basis.

[b] The real annual discount rate (d') equivalent to the nominal discount rate (d) for any given general inflation rate (G) can be computed as

$$d' = \frac{1 + d}{1 + G} - 1.$$

Conversely, the nominal discount rate equivalent to the real discount rate for any given general inflation rate can be computed as

$$d = (1 + d')\,(1 + G) - 1.$$

For example, a 2 percent discount rate and a 10 percent rate of general inflation result in a 12.2 percent nominal discount rate (1.02 x 1.10 -1 = 0.122).

Table A-2. Present Value of Interest Payments per $1000 Borrowed[a]

(Discounted from end of year)

Discount Rate (Nominal)[b]	Mortgage Life (years)	Interest Rate (Nominal) 9%	10%	11%	12%	13%	14%	15%	16%	17%	18%
	20	596	672	750	829	909	990	1072	1155	1239	1323
10%	25	677	763	851	939	1029	1119	1210	1302	1393	1486
	30	738	831	925	1020	1116	1211	1308	1404	1500	1597
	20	537	605	674	744	815	888	960	1034	1108	1182
12%	25	600	675	752	829	907	986	1065	1145	1224	1304
	30	645	725	806	888	970	1052	1135	1217	1300	1382
	20	487	548	610	673	737	802	867	932	998	1065
14%	25	536	603	671	739	808	878	947	1017	1088	1158
	30	517	641	712	783	855	926	998	1070	1142	1214
	20	445	500	556	613	671	729	788	847	906	966
16%	25	484	544	605	666	727	789	851	913	976	1038
	30	511	573	636	699	762	825	889	952	1016	1079
	20	377	423	470	518	566	614	663	712	761	811
20%	25	404	453	502	552	602	653	703	754	805	856
	30	420	471	522	572	623	675	726	777	828	879

[a] Calculation Procedure: P.V. Interest Payments = $$\sum_{j=1}^{n} \frac{\sum_{k=1}^{12} \frac{i}{12} \cdot L_{(k+12(j-1))}}{(1+d)^j}$$

where $L_{(k+12(j-1))} = L_{(k-1+12(j-1))}(1 + i/12) - P$,

i = annual interest rate,
L_o = initial loan amount,
$L_{(k+12(j-1))}$ = remaining principal at end of month $(k + 12(j-1))$,
P = uniform monthly payment,
d = discount rate, and
n = loan life in years.

In closed form, the P.V. of interest paymenst, discounted from the end of the year, can be calculated as:

$$\text{P.V. Interest Payments} = L_o \left[12 \cdot CRF \cdot UPW - \left(\frac{CRF}{i/12} - 1\right)\left(1 - \frac{1}{(1+i/12)^{12}}\right)\left(\frac{(1+d1)^n - 1}{d1\,(1+d1)^n}\right)\right]$$

where $CRF = (i/12)(1 + i/12)^{12n}/((1 + i/12)^{12n} - 1)$

$UPW = ((1 + d)^n - 1)/(d(1+d)^n)$

$d1 = [(1 + d)/(1 + i/12)^{12}] - 1$

[b] See footnote b on table A-1

Table A-3. Modified Uniform Present Worth Factors (UPW*)

Discount Rate	Rate of Fuel Price Increase	Building Lifetime (years)				
		20	25	30	35	40
0%	0%	20.0	25.0	30.0	35.0	40.0
	2%	24.8	32.7	41.4	51.0	61.6
	4%	31.0	43.3	58.3	76.6	98.8
	6%	39.0	58.2	83.8	118.1	164.0
	8%	49.4	79.0	122.3	186.1	279.8
	10%	63.0	108.2	180.9	298.1	486.9
	12%	80.7	149.3	270.3	483.5	859.1
		20	25	30	35	40
2%	0%	16.4	19.5	22.4	25.0	27.4
	2%	20.0	25.0	30.0	35.0	40.0
	4%	24.7	32.5	41.1	50.6	61.1
	6%	30.7	42.8	57.5	75.3	96.9
	8%	38.5	57.1	82.0	115.1	159.1
	10%	48.5	77.1	118.7	179.5	268.1
	12%	61.5	104.9	174.0	284.5	460.8
		20	25	30	35	40
4%	0%	13.6	15.6	17.3	18.7	19.8
	2%	16.4	19.6	22.5	25.2	27.5
	4%	20.0	25.0	30.0	35.0	40.0
	6%	24.6	32.3	40.9	50.2	60.5
	8%	30.4	42.4	56.8	74.2	95.2
	10%	38.0	56.2	80.3	112.2	154.5
	12%	47.6	75.3	115.3	173.3	257.3
		20	25	30	35	40
6%	0%	11.5	12.8	13.8	14.5	15.0
	2%	13.7	15.8	17.5	18.9	20.0
	4%	16.5	19.7	22.6	25.3	27.7
	6%	20.0	25.0	30.0	35.0	40.0
	8%	24.5	32.2	40.6	49.9	60.1
	10%	30.2	41.9	56.0	73.0	93.5
	12%	37.5	55.3	78.7	109.6	150.2
		20	25	30	35	40
10%	0%	8.5	9.1	9.4	9.6	9.8
	2%	9.9	10.8	11.4	11.8	12.1
	4%	11.7	13.1	14.1	14.9	15.5
	6%	13.9	16.0	17.8	19.3	20.5
	8%	16.6	19.9	22.9	25.6	28.1
	10%	20.0	25.0	30.0	35.0	40.0
	12%	24.3	31.9	40.1	49.2	59.1

Table A-4. Unit Energy Prices (Metered) and Corresponding Price per Million Btu Output from Furnace

A. Price per Million Btu Metered (P_H/η_H) for Selected Fuel Types

Fuel Type	Price Unit	Unit Energy Price ($)									
Gas	therm	0.20	0.30	0.40	0.60	0.80	1.00	1.20	1.50	1.80	2.20
Oil	gallon	0.28	0.42	0.56	0.84	1.12	1.40	1.68	2.10	2.52	3.08
Elec.	kWh	0.007	0.010	1.014	0.021	0.027	0.034	0.041	0.051	0.061	0.075
$/Million Btu (metered)		2.00	3.00	4.00	6.00	8.00	10.00	12.00	15.00	18.00	22.00

B. Price per Million Btu Output for Selected Furnace Efficiencies

Furnace Efficiency[a]	Price per Million Btu Metered (P_H/η_H) 2.00	3.00	4.00	6.00	8.00	10.00	12.00	15.00	18.00	22.00
0.6	3.33	5.00	6.67	10.00	13.33	16.67	20.00	25.00	30.00	36.67
0.7	2.86	4.29	5.71	8.57	11.43	14.29	17.14	21.43	25.71	31.43
0.8	2.56	3.75	5.00	7.50	10.00	12.56	15.00	18.75	22.50	27.50
0.9	2.22	3.33	4.44	6.67	8.89	11.11	13.33	16.67	20.00	24.44
1.0	2.00	3.00	4.00	6.00	8.00	10.00	12.00	15.00	18.00	22.00
1.4	1.43	2.14	2.86	4.49	5.71	7.14	8.57	10.71	12.86	15.71
1.6	1.25	1.88	2.50	3.75	5.00	6.25	7.50	9.38	11.25	13.75
1.8	1.11	1.67	2.22	3.33	4.44	5.56	6.67	8.33	10.00	12.22
2.0	1.00	1.50	2.00	3.00	4.00	5.00	6.00	7.50	9.00	11.00
2.2	0.91	1.36	1.82	2.73	3.64	4.55	5.45	6.82	8.18	10.00

[a] Efficiencies greater than 1.0 are for heat pumps.

Table A-5. Selected kWh Prices and Equivalent Price per Million Btu Output for Selected Central Air Conditioner (CAC) Efficiencies

CAC Efficiency		Metered kWh Price					
		$0.021	$0.034	$0.048	$0.061	$0.075	$0.089
		Equivalent Input Cost per Million Btu					
		$6.00	$10.00	$14.00	$18.00	$22.00	$26.00
		Equivalent Output Cost per Million Btu (Price per Million Btu for Selected CAC Efficiencies)					
COP	SEER						
1.75	6	3.43	5.71	8.00	10.29	12.57	14.86
2.05	7	2.93	4.88	6.83	8.78	10.73	12.68
2.35	8	2.55	4.26	5.96	7.66	9.36	11.06
2.65	9	2.26	3.77	5.28	6.79	8.30	9.81
2.95	10	2.03	3.39	4.75	6.10	7.46	8.81
3.20	11	1.87	3.13	4.38	5.63	6.88	8.13

APPENDIX B

ESTIMATING PRESENT-VALUE LIFE-CYCLE TAX AND INSURANCE COSTS

In general, improvements in the design of a building to reduce its energy consumption requirements can be expected to increase the value of that building. Such an increase in value is essential to the life-cycle-cost concept if the building is to be sold during its useful life. Estimates of the increase in value are important, even if the building is not sold, because future property tax liabilities and insurance premium will be based on estimated property values in the years to come. These additional costs should be considered in a complete evaluation of the incremental costs of energy conservation improvements on a life cycle basis.

In a life-cycle cost context, the increase in building value due to energy conservation improvement at any given point in time is equal to the net discounted value of future energy savings over the remaining lifetime of the conservation improvement, or to the replacement cost of that improvement, whichever is lower. However, the net discounted value of the remaining energy savings is not simply the discounted sum of the future dollar reduction in fuel bills. Future tax and insurance costs which are incurred because of the increased building value must be considered as well in that they reduce the net present value of the remaining energy savings.

Tax liabilities and insurance premiums payable at the beginning of years i (T_i and I_i) can be stated as:

$$T_i = \text{MIN}\ (R_T \cdot NPVES_i,\ R_T \cdot C_i) \tag{B-1}$$

and

$$I_i = \text{MIN}\ (R_I \cdot NPVES_i,\ R_I \cdot C_i) \tag{B-2}$$

where

R_T = property tax rate,
R_I = insurance premium rate,
$NPVES_i$ = net present value at the beginning of year i of energy savings over the remaining life of the building, and
C_i = replacement cost at beginning of year i.

Both R_T and R_I are assumed to be constant over the life of the building. Taxes and insurance liabilities are assumed to be payable at the beginning of each period and are calculated using energy and replacement costs at that same time.

Total present-value, life-cycle property tax and insurance premium (TI) can thus be expressed as

$$TI = \sum_{i=1}^{L} \text{MIN}[R \cdot NPVES_{i},\ R \cdot C_i]/(1 + D)^{i-1}, \tag{B-3}$$

where $R = R_T + R_I$,
D = the real discount rate, and
L = the expected useful lifetime.

It is assumed that the replacement cost at any given time is equal to the additional construction cost in constant dollar terms. However, for some modifications (as with walls of increased thickness) this will not be the case and thus replacement costs will be understated.

In order to calculate ($R \cdot NPVES_i$), a recursive system of equations must be established. That is, the taxes and insurance costs that are incurred in one year depend on the taxes and costs incurred in the next. Thus the calculation procedure must begin with the last year of the expected useful life and work backwards to the first year. Taxes and insurance costs can be estimated in this manner for each year over the useful life. This recursive system of equations reduces to a manageable form that can be calculated on a computer without great difficulty.

Beginning with year L, tax and insurance costs (incurred at the beginning of the year) can be calculated as follows:

$$R \cdot NPVES_L = S_o \cdot R \cdot \frac{(1+P)^{L-1}}{1+R} = S_o \ (1+P)^{L-1} - \frac{(1+P)^{L-1}}{(1+R)} \qquad \text{(B-4)}$$

where S_o = average annual energy savings valued in current dollars at beginning of year 1.

Working backwards for each year L, L-1, L-2, . . ., 1, a generalized form appears:

$$R \cdot NPVES_{L=1} = S_o \ \frac{\frac{(1+P)^{L-1}}{1+R} - \frac{(1+P)^{L-1}}{(1+R)^2}}{1+D} + (1+P)^{L-2} - \frac{(1+P)^{L-2}}{1+R} \qquad \text{(B-5)}$$

$$R \cdot NPVES_{L-k} = S_o \ \frac{\frac{(1+P)^{L-1}}{(1+R)^k} - \frac{(1+P)^{L-1}}{(1+R)}}{(1+D)^k} + (1+P)^{L-k-1} - \frac{(1+P)^{L-k-1}}{1+R} \qquad \text{(B-6)}$$

or, where $i = L - k$,

$$R \cdot NPVES_i = S_o \cdot \sum_{j-i}^{L} \frac{\frac{(1+P)^{j-1}}{(1+R)^{j-i}} - \frac{(1+P)^{j-1}}{(1+R)^{j-i+1}}}{(1+D)^{j-1}} \qquad \text{(B-7)}$$

$$R \cdot NPVES_i = S_o \cdot \frac{R(1+D)^{i-1}}{(1+R)^{2-i}} \cdot \sum_{j=i}^{L} A^{j-1} , \qquad \text{(B.8)}$$

where $A = \dfrac{1 + P}{(1 + R)(1 + D)}$, and

$$R \cdot NPVES_i = S_o \cdot R(1 + D)^{i-1} \cdot (1 + R)^{i-2} \cdot \frac{A^{i-1} - A^L}{1 - A} \qquad (B.9)$$

This procedure permits the calculation of the present value of life-cycle property tax and insurance premiums based on the increased value of the building due to its energy conservation features. However, no generalized factors for estimating tax and insurance costs as a function of increased construction cost (or sales price) can be established because the ratio of dollar energy savings to increased construction costs varies widely from modification to modification.

In the economic analysis of energy conservation improvements, the critical point of evaluation is where the ratio of incremental savings to incremental costs (adjusted for tax and insurance liabilities) is equal to one. Given such a constant ratio, a generalized factor can be established which is useful in determining whether a given conservation improvement has a benefit/cost ratio greater than unity. That is, if the ratio of savings to cost is still greater than unity after adjustment for taxes and insurance, the modification is assumed to be cost effective. Thus, a factor to adjust for taxes and insurance, based on the assumption that net incremental savings must be at least equal to net incremental costs in order to be cost effective, will serve as a check to assure cost effectiveness consistent with the general assumptions made. Table B-1 provides such adjustment factors for a range of net tax rates and insurance rates, lifetimes, real energy price escalation rates, and real discount rates. Interpolation can be used to find factors for intermediate values of these variables. Increasing first costs by this factor will provide an adjusted cost for comparison with present-value savings.

It should be recognized that these factors will likely overstate the actual increase in property taxes over the life of the building because energy conservation modifications are frequently not considered in the assessed value of a house. However, if assessed values are based on the selling price of a house, and that selling price reflects the true value of its energy conservation features, these factors will serve as reasonable estimators.

Table B-1. Present Value Factors for Estimating Future Property Taxes and Insurance Costs[a]

Discount Rate (Real, %)	Building Life (Years)	Energy Price Increase Rate (Real, %)	Net Tax Rate Plus Insurance Rate[b] 1%	2%	3%	4%
0	20	0	.11	.22	.32	.40
		2	.11	.23	.34	.42
		4	.12	.24	.36	.45
	30	0	.16	.34	.50	.61
		2	.17	.36	.54	.66
		4	.19	.39	.58	.71
	40	0	.22	.46	.70	.84
		2	.24	.52	.79	.93
		4	.27	.57	.86	1.02
2	20	0	.10	.21	.31	.39
		2	.11	.22	.33	.41
		4	.11	.23	.35	.44
	30	0	.15	.31	.46	.57
		2	.16	.33	.51	.62
		4	.17	.36	.56	.68
	40	0	.19	.40	.62	.77
		2	.22	.46	.71	.87
		4	.24	.50	.76	.96
4	20	0	.10	.20	.30	.37
		2	.10	.21	.32	.40
		4	.11	.22	.34	.42
	30	0	.13	.28	.42	.53
		2	.14	.31	.47	.59
		4	.16	.33	.50	.64
	40	0	.17	.34	.52	.70
		2	.19	.38	.58	.77
		4	.20	.39	.59	.79
6	20	0	.09	.19	.28	.36
		2	.10	.20	.30	.38
		4	.10	.21	.32	.41
	30	0	.12	.24	.38	.50
		2	.13	.27	.41	.54
		4	.14	.28	.42	.56
	40	0	.14	.29	.44	.59
		2	.15	.31	.46	.62
		4	.16	.31	.47	.62
10	20	0	.08	.16	.25	.33
		2	.08	.17	.26	.34
		4	.09	.18	.27	.36
	30	0	.10	.20	.30	.40
		2	.10	.20	.30	.41
		4	.10	.20	.31	.41
	40	0	.10	.21	.32	.42
		2	.11	.21	.32	.43
		4	.11	.21	.32	.43

[a] Multiply present value factor by first cost to estimate present value of increased property taxes and insurance over the specified building life.

[b] Net tax rate is the property tax rate as applied to the actual house value and adjusted for income tax credit. (For example, in the 20 percent tax bracket a 2.5 percent property tax rate becomes 2 percent (=2.5 x (1-.2).)

Table B-2. Residential Property Tax Rates in Selected Large Cities: 1977

City	Effective Tax Rate per $100 of Actual Value
Boston	$7.84
Indianapolis	4.23
Detroit	3.71
Milwaukee	3.59
Philadelphia	3.09
Los Angeles	2.94
San Francisco	2.80
Baltimore	2.76
Dallas	2.68
San Antonio	2.48
San Jose	2.46
Houston	2.44
Atlanta	2.39
Pittsburgh	2.36
St. Louis	2.14
San Diego	2.13
Cleveland	1.97
Memphis	1.94
New York City	1.93
Washington, D.C.	1.80
Seattle	1.76
Phoenix	1.73
Chicago	1.71
Jacksonville	1.67
Kansas City, Mo.	1.35
Nashville	1.28
Columbus, Ohio	1.27
Denver	1.16
New Orleans	0.96
Honolulu	0.82

Source: U.S. Bureau of the Census, <u>Statistical Abstract of the United States: 1979</u> (100th edition), Washington, D.C., 1979, Table 508, p. 312.

APPENDIX C

LONG-TERM HEATING DEGREE-DAY MAPS AND COOLING DEGREE HOUR DATA

NORMAL SEASONAL HEATING DEGREE DAYS - BASE 65° F

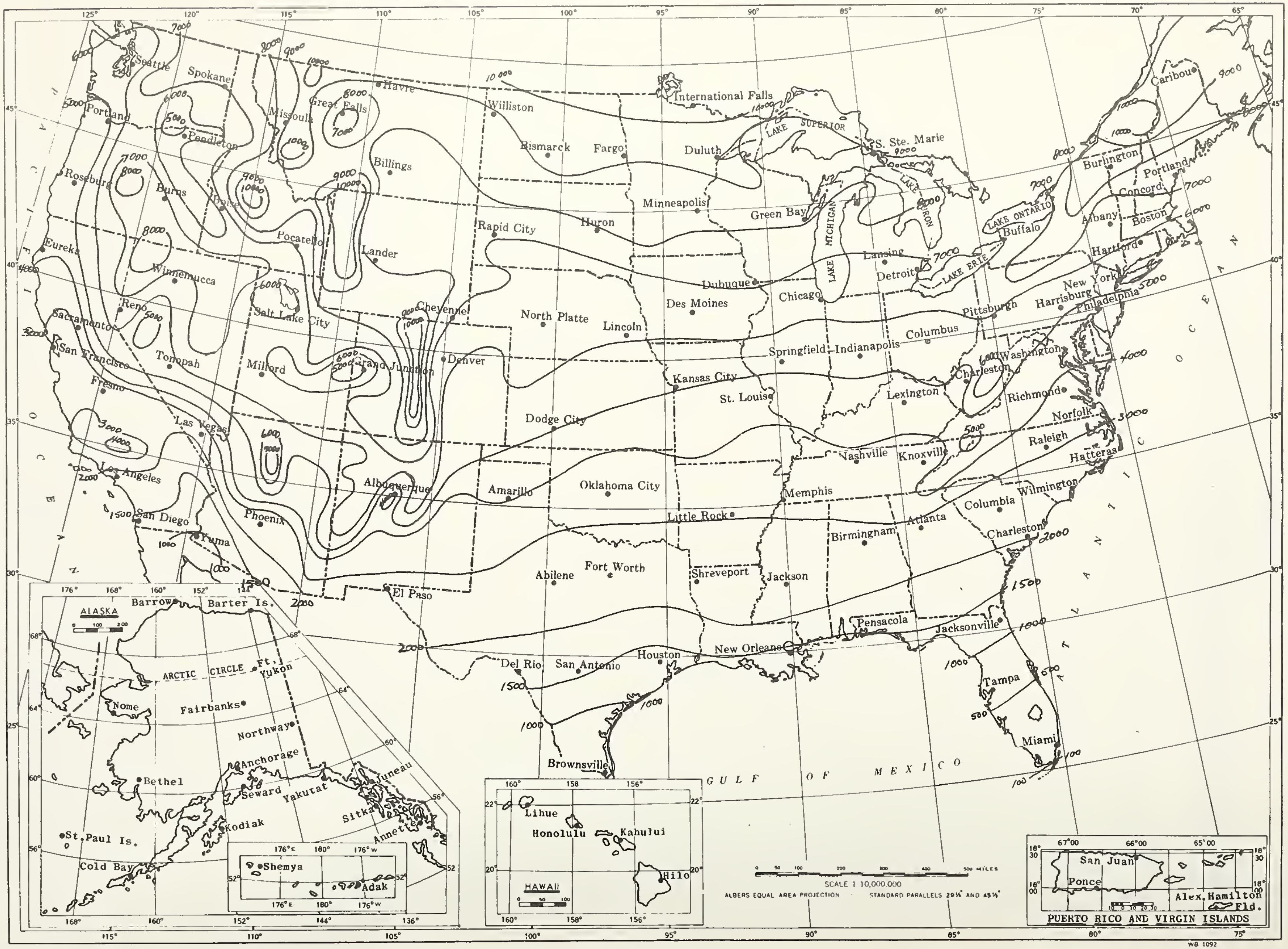

Figure C-1 Normal Seasonal Heating Degree Days - Base 65°F

NORMAL SEASONAL HEATING DEGREE DAYS - BASE 60° F

Figure C-2 Normal Seasonal Heating Degree Days - Base 60°F

NORMAL SEASONAL HEATING DEGREE DAYS - BASE 55° F

Figure C-3 Normal Seasonal Heating Degree Days - Base 55°F

NORMAL SEASONAL HEATING DEGREE DAYS - BASE 50° F

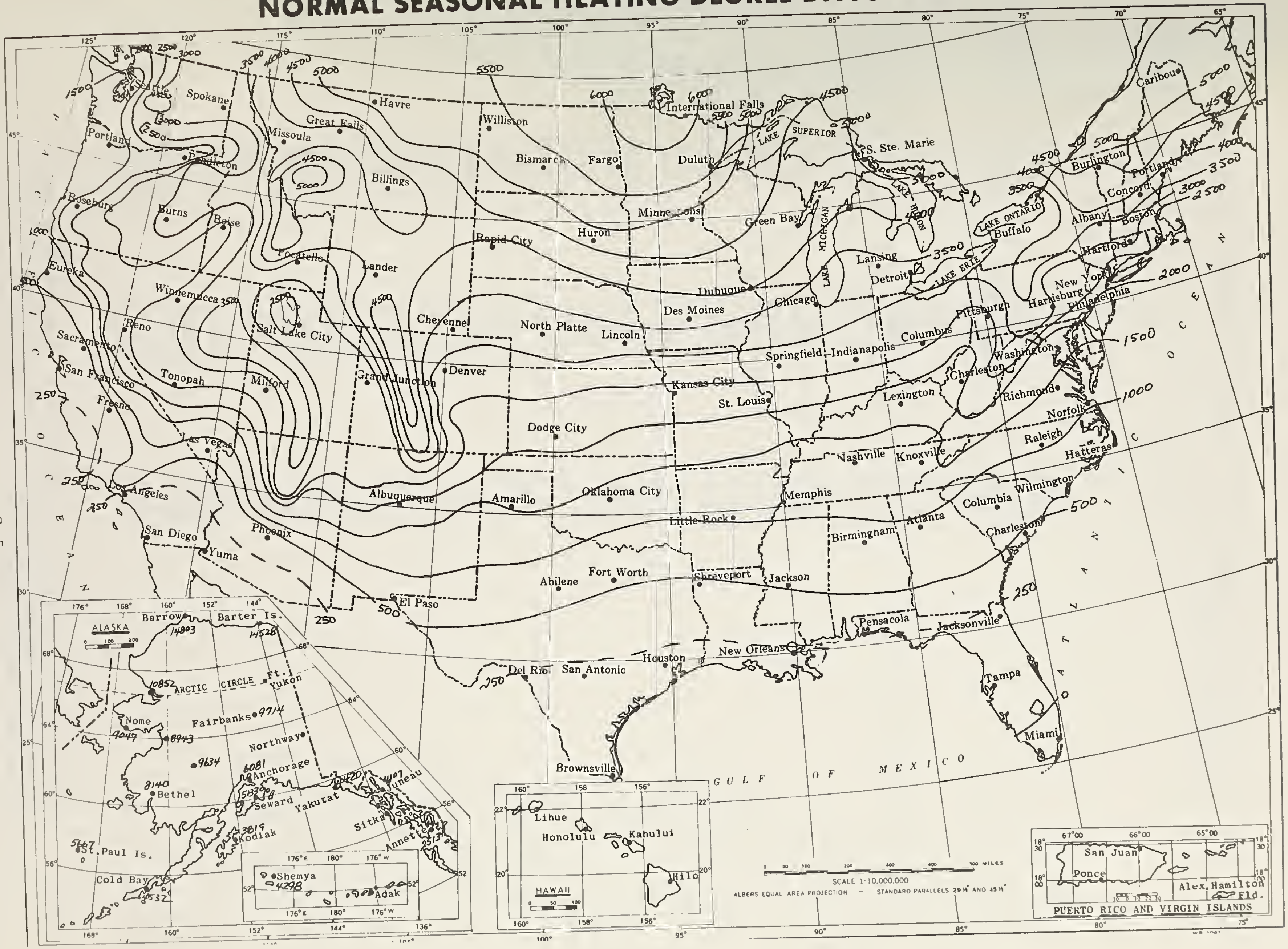

Figure C-4 Normal Seasonal Heating Degree Days - Base 50°F

Table C-1. Long Term Cooling Degree Hour Data for Selected Cities and Calculation Bases[a]

CITY	$CDH_{72.5}$	CDH_{75}	$CDH_{77.5}$
Albany, NY	7500	5100	3400
Albuquerque, NM	19600	14800	10800
Atlanta, GA	20700	14800	10300
Bakersfield, CA	33600	26800	21000
Baltimore, MD	14200	10100	6900
Boston, MA	7500	5100	3300
Chicago, IL	12500	8900	6200
Columbus, OH	12400	8800	6000
Dallas, TX	41600	32900	25500
Denver, CO	11200	8100	5700
Des Moines, IA	12500	9000	6200
Detroit, MI	9000	6100	4000
El Paso, TX	35000	27300	20900
Fort Worth ,TX	37400	29300	22400
Indianapolis, IN	12300	8600	5700
Kansas City, KS	23500	17900	13200
Little Rock, AR	28200	21400	15700
Los Angeles, CA	4000	2200	1200
Louisville, KY	19200	14100	10000
Madison, WI	8400	5800	3800
Memphis, TN	27200	20500	15100
Miami, OH	44500	30800	19800
Milwaukee, WI	6400	4300	2700
Minneapolis, MN	8700	6000	3900
New Orleans, LA	31300	22100	14900
New York, NY	44500	30800	19800
Oklahoma City, OK	25200	19300	14400
Philadelphia, PA	12600	8700	5800
Phoenix, AZ	60600	50600	41700
Pittsburgh, PA	7300	4700	2800
Richmond, VA	17600	12800	9100
Sacramento, CA	17300	13400	10200
Salt Lake City, UT	16000	12300	9200
San Antonio, CA	39400	30100	22400
San Diego, CA	4300	2300	1200
San Francisco, CA	1300	800	500
Savannah, GA	26200	18800	13100
Seattle, WA	1800	1100	700
Tampa, FL	35000	24500	16300
Topeka, KS	20600	15600	11600
Washington, DC	16100	11400	7800

[a] Source: Calculated from National Climatic Center Summary Sheets: "Frequency of Hourly Temperatures" See Attachment C-1 for calculations methodology.

Attachment C-1. Methodology Used to Calculate Cooling Degree Hours

Cooling degree hours for any seleccted base temperature can be calculated directly using

$$\sum_{i=B+1}^{M} (i - B)F_i,$$

where B = base temperature
M = maximum outdoor temperature
F_i = frequency of hourly temperature i in average year.

If frequency of hourly temperatures is only available in 5°F temperature intervals, $T_{i,i+4}$ (e.g. T_{60-64}, T_{65-70}, ...), F_i can be approximated using the following relationships:

$$F_i = 0.4(T_{i-5,i-1}/5) + 0.6(T_{i,i+4}/5)$$

$$F_i = 0.2(T_{i-5,i-1}/5) + 0.8(T_{i,i+4}/5)$$

$$F_{i+2} = T_{i,i+4}/5$$

$$F_{i+3} = 0.8(T_{i,i+4}/5) + 0.2(T_{i+5,i+9}/5)$$

$$F_{i+4} = 0.6(T_{i,i+4}/5) + 0.4(T_{i+5,i+9}/5)$$

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

This report investigates the extent to which certain energy conservation modifications to the envelope design of a new, single-family house are economically justified for a wide range of climates and projected energy costs. The report provides background information on those factors that give rise to space heating and cooling loads in buildings and examines in greater detail than in previous reports the thermal interdependencies within and among envelope components that can greatly affect heating and cooling loads. Economic criteria for determining a minimum life-cycle cost building envelope design are formulated and a priority-ranking method is developed to assist in the calculation of these designs. An expanded version of the NBS Load Determination Program is used to calculate the annual heating and cooling requirements and maximum heating and cooling loads for a 1200 square foot, wood-frame house having a wide range of thermal improvements in 14 geographic locations. The report also provides a methodology for interpolating these results to climatic conditions other than the 14 analyzed. The analysis demonstrates that the optimal envelope design configuration varies over a wide range depending on climate, energy costs, and modification costs.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Architecture; building design; cost-benefit analysis; economics; energy conservation; housing; insulation; space heating and cooling costs; space heating and cooling requirements

13. AVAILABILITY

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